EFFECTS OF EXCHANGEABLE SOIL CALCIUM, MAGNESIUM AND CALCIUM/MAGNESIUM RATIOS ON PLANT NUTRITION AND GROWTH OF LETTUCE ON AN ULTISOL

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To My Past 22 Years

of Study and Research on

Agronomy and Soil Science

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ABSTRACT

Two greenhouse pot experiments were conducted to study the effects of exchangeable soil calcium, magnesium and calcium/magnesium ratios on nutrition and growth of lettuce (*Lactuca sativa* L.) on an Ultisol (Manana soil series) with low pH (4.35), Ca (0.57 $cmol_c$ kg^{-1}) and Mg (0.60 $cmol_c$ kg^{-1}) in Hawaii to obtain calibration data for Ca and Mg in Hawaii soils and test the current sufficiency recommendations for Ca and Mg for making fertilizer recommendations. The objectives of this study were: to identify the sufficiency levels of exchangeable soil Ca and Mg for growth of lettuce; to investigate the validity of an ideal Ca/Mg ratio for growth of lettuce and to determine the effects of soil Ca and Mg levels as well as Ca/Mg ratios on soil nutrients and the nutrition and growth of lettuce. Lettuce yield increased as soil Ca increased and also as plant Ca level increased. The Cate-Nelson method was applied to determine the critical levels of Ca, Mg and the Ca/Mg ratio in the soil and plant. A critical soil Ca level for lettuce was determined to be 1.9 $cmol_c$ kg^{-1} and is more reasonable and lower than the value of 5 $cmol_c$ kg^{-1} that is currently recommended in Hawaii. Lettuce in the zero Ca treatment with 0.57 $cmol_c$ kg^{-1} soil Ca exhibited Ca deficiency symptoms in the Ca experiment. A critical plant Ca concentration for lettuce at maturity was also determined to be 4 g kg^{-1}. Exchangeable soil cations interact with each other and application of a large amount of liming material can cause cation imbalance. In the Ca experiment, soil Mg, K and Na decreased as soil Ca increased. Application of Ca increased the soil Ca level, increased Ca uptake by the plant and reduced the uptake of Mg and Na but had no effect on the uptake of P. Soil Ca restricted K uptake at low Ca levels due to decreased ion selectivity and leakiness of membranes

membranes when Ca was deficient. Lettuce growth was normal with all soil Mg levels in the Mg experiment. Lettuce yield also was not related to plant Mg level. A critical soil Mg level for lettuce could not be established, however, the soil Mg level of the zero Mg treatment, 0.67 $cmol_c\ kg^{-1}$, was apparently adequate for normal lettuce growth. Therefore, the sufficiency range for soil Mg recommended in Hawaii (2.5 to 3.3 $cmol_c\ kg^{-1}$) appears too high. Lettuce in the zero Mg treatment did not show any Mg deficiency symptoms. A critical plant Mg concentration for lettuce at maturity also could not be determined, however, the plant Mg concentration of the zero Mg treatment, 4 $g\ kg^{-1}$, was apparently sufficient for normal growth of lettuce. Interactions between soil cations also occurred in the Mg experiment where soil Ca, K, and Na decreased as soil Mg increased. Increased levels of soil Mg increased the uptake of Mg by the plant, and reduced the uptake of Ca and Na, but had no effect on the uptake of K and P. In the soil Ca/Mg ratios ranged from 0.11 to 7.70, lettuce growth was limited by a Ca/Mg ratio of around 0.11 and no yield reduction was observed in the Ca/Mg ratio range from 0.50 to 7.70, which is within the optimal range. This study provides evidence for the conclusion that plants can grow normally within a broad range of Ca/Mg ratios. Lettuce yield was related to both soil Ca/Mg ratio and plant Ca/Mg ratio. The lower critical level of the soil Ca/Mg ratio for lettuce was determined to be 0.5. However, caution should be used in interpreting yield response to the soil Ca/Mg ratio because soil Ca or Mg levels can also affect plant growth. The critical plant Ca/Mg concentration ratio for lettuce at maturity was also determined to be 0.5. Plant Ca/Mg ratios in lettuce were significantly related to soil Ca/Mg ratios.

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CHAPTER 1

INTRODUCTION

In the past two decades, diversified crops have gradually grown on a large acreage of former sugar and pineapple land in Hawaii due to economic and social development. Many diversified crops are not tolerant to acid soil and require liming to reduce soil acidity. Most vegetable crops require soil pH> 5.5 and many vegetables popular in Hawaii, such as cabbage, spinach, celery, lettuce, onion and cauliflower prefer soil pH>6.0 (Swiader et al., 1992). Soil Ca and Mg are likely to be deficient for vegetables grown on acid soils in areas of moderate to high rainfall or when large amounts of Mg or Ca based lime and/or K fertilizer have been applied. This applies especially to Ca and Mg sensitive crops such as carrots, celery, tomatoes, and spinach (Swiader et al., 1992; von Uexkull, 1986; Adams, 1984). In Hawaii, soils developed from coral sand or coral parent materials are also likely to be Mg deficient. Information on the sufficiency levels of soil Ca and Mg for vegetable crops is critical for an effective fertilizer and lime recommendation system to ensure optimal growth of diversified vegetable crops in Hawaii.

Many researchers have reported that sufficient levels of exchangeable soil Ca and Mg are essential for providing adequate Ca and Mg nutrients for maximum crop yield. Critical or sufficiency levels of soil Ca (Kamprath, 1984; Melsted, 1953; McLean, 1982; Andrew and Norris, 1961; Haby et al., 1990) and soil Mg (Adams, 1984; McLean, 1982; McLean and Carbonell, 1972; Fox and Piekielek, 1984; Haby et al., 1990) have been established by researchers around the United States in different soils and regional growth conditions for different crops.

However, little information is available on the sufficiency levels of exchangeable soil Ca and Mg for crops grown on acid soils in Hawaii. The critical or sufficient Ca and Mg levels at which crops are no longer expected to respond to Ca and Mg application established by the above researchers were 1 to 3 $cmol_c\ kg^{-1}$ for Ca and 0.06 to 0.6 $cmol_c\ kg^{-1}$ for Mg in the US. However, in Hawaii, soil Ca and Mg sufficiency levels for fertilizer and lime recommendations (Tamimi et al., 1994) are much higher. The sufficient Ca levels are 7.5 to 10 $cmol_c\ kg^{-1}$ for heavy soils with bulk density close to 1.0 $g\ cm^{-3}$ and 15 to 20 $cmol_c\ kg^{-1}$ for light soils with bulk density close to 0.5 $g\ cm^{-3}$. Mg sufficient levels are believed to be 2.5 to 3.3 and 5 to 6.7 $cmol_c\ kg^{-1}$ for heavy and light soils, respectively. Tamimi et al. (1994) also recommended a Ca/Mg ratio of 3 on the basis of $cmol_c\ kg^{-1}$. The sufficient Ca level for heavy soils has been updated recently (Yost., 1999) to 5 to 7.5 $cmol_c\ kg^{-1}$. Since the critical or sufficiency levels of Ca and Mg vary greatly with soil types, regional growing conditions and crops, it is often necessary to carry out correlation and calibration studies under local conditions to establish satisfactory critical or sufficient levels of Ca and Mg. Unfortunately, there is a lack of such studies in Hawaii to support establishing sufficiency levels of Ca and Mg.

Most liming materials are Ca-based and excess Ca applied to soil can induce Mg and K deficiency. In a number of field trails in Alabama, liming with a high grade calcitic material caused Mg deficiency where none existed before liming (Adams, 1975). More evidence of substantial reductions in exchangeable Mg with liming was obtained by Sumner et al. (1978); Sims and Ellis (1983); Farina et al. (1980); Chan et al. (1979);

Grove and Sumner (1985) and Myers et al. (1988). Sumner et al. (1978) and Grove and Sumner (1985) suggested that limited Mg availability may be a contributing factor in yield reductions commonly observed when acid soils are limed to near neutrality. On the other hand, using Mg-based lime may induce Ca deficiency or cause Mg toxicity. On an acid Brazilian Oxisol, liming with $MgCO_3$ resulted in an average soybean grain yield of less than 100 kg ha^{-1} while liming with $CaCO_3$ produced an average yield of 2100 kg ha^{-1} (Souza and Ritchey, 1988). The authors suggested that when $MgCO_3$ was applied, excessive soil Mg in relation to soil Ca resulted in a Ca/Mg ratio less than 1.0, which caused the low yields. Calcium deficiency of barley was also reported due to over liming with $MgCO_3$ in a Latosol of South China (Gong, et al., 1981).

There is apparently a lack of calibration data for Ca and Mg in Hawaii soils and a need to test the current sufficiency recommendations for Ca and Mg. These data are required to allow reliable fertilizer recommendations to be made for soil and tissue samples sent in for analysis and recommendations. Therefore, research was carried out to achieve the following objectives:

1. To identify the sufficiency levels of exchangeable soil Ca and Mg for growth of lettuce on an acid Tropical soil.

2. To investigate the validity of an ideal cation ratio of Ca/Mg for growth of lettuce on an acid Tropical soil.

3. To determine the effects of soil Ca and Mg levels as well as Ca/Mg ratios on soil nutrients and the nutrition and growth of lettuce.

CHAPTER 2

LITERATURE REVIEW

Soil testing methods for exchangeable soil Ca and Mg

Exchangeable Ca and Mg are the major reserves of soil Ca and Mg available to plant roots. The most common extractant for determining what is considered exchangeable Ca and Mg from soil is molar ammonium acetate at pH 7.0 (Thomas, 1982; Haby et al., 1990; Soil and Plant Analysis Council, Inc., 1992). The other common extractants are Mehlich No1 (Double Acid), Mehlich No.2, Mehlich No.3, Morgan and water which are discussed and described in the Handbook on Reference Methods for Soil Analysis (Soil and Plant Analysis Council, Inc., 1992).

The validity of a soil test method is based on calibration studies for crops under local soil and environmental conditions. The common soil test methods for exchangeable soil Ca and Mg were originally based on calibration studies for exchangeable K because Ca and Mg are generally less limiting than K in most soils. A limited number of calibration studies for soil Ca and Mg testing methods are found in the literature. Moreover, methods for testing for exchangeable Ca, which is used to predict the availability of Ca to plants, have not received the attention extended to those for Mg because Ca availability to plants is not a problem in alkaline soils and application of Ca based liming materials to acid soils provides adequate Ca for plant growth. In contrast to Ca, research on soil test methods for Mg has been relatively extensive because of the need to predict crop yield response to applied Mg and to predict Mg uptake by plants to prevent hypomagnesemia in ruminant animals (Haby et al., 1990).

A survey of 43 universities (Eckert, 1987) showed that 22 universities used in-state research, 14 universities used neighboring state results and 11 universities used literature information to make soil Ca interpretations and recommendations. It also showed that 25 universities used in-state research, 20 universities used neighboring state results and 13 universities used literature information to make soil Mg interpretations and recommendations. This indicates that in the United States soil test and interpretation systems for Ca and Mg were heavily based on data from outside the state. In Hawaii, molar ammonium acetate at pH 7.0 has been used for a long time as an extractant for exchangeable soil K, Ca and Mg. However, little information is available to evaluate this method for predicting the availability of soil Ca and Mg to plants in Hawaii soils.

Interpretation of Soil Test for Ca and Mg

Currently, two philosophies are dominant in the soil test interpretation for Ca and Mg. The "sufficiency level" or "critical level" promotes the concept that there are definable levels of individual nutrients such as Ca and Mg in the soil below which plants will respond to applied nutrients with some probability and above which they likely will not respond. Two approaches, the sufficiency level approach and the graphical approach, are most commonly used by agronomists to identify the critical level for nutrients. The other philosophy, "basic cation saturation ratio" (BCSR) or "cation ratio" proposes that maximum yields can be obtained by creating an ideal ratio of cations such as Ca/Mg in the soil.

In the United States, most public laboratories such as university labs use sufficiency level interpretations (McLean, 1977, Eckert, 1987) while private laboratories prefer the cation ratio concept (McLean, 1977; Liebhardt, 1981).

Sufficiency Level Approach

The concept of sufficiency levels as a basis for interpreting soil tests can largely be credited to the work of Bray in Illinois (Bray, 1944, 1945). Bray related crop yields to various fertilizer treatments using a modification of the Mitscherlich equation

$$\log (A-y) = \log A - c_1x_1 - c_2x_2$$

where A = maximum obtained yield, y = any observed yield, x_1 = measured soil nutrient level, x_2 = quantity of added nutrient, and c_1 and c_2 = proportionality constants for x_1 and x_2.

When A, y, c_1 and c_2 are determined using field data, the equation can provide two important pieces of information: the sufficiency level itself and the amount of fertilizer required to achieve optimum yields if the soil test level falls below the sufficiency level. This method uses the regression approach to establish a relationship between soil test and yield response to fertilizer. The concepts of maximum yield, relating yields to soil tests mathematically, and using soil tests to predict the probability of response to added fertilizer have had a profound effect on present thinking. Since his original proposal was made, the concept of Bray has been adopted, expanded, and modified to fit specific situations, as needs have arisen. Quadratic and logarithmic mathematical models have been used to describe the relationship between soil nutrient levels and yield responses to added fertilizer.

Graphical Approach

In contrast to mathematically determining soil test correlation, Cate and Nelson

(1965) developed a simple graphical method to interpret soil tests. This simple method may produce results as satisfying as more complex regression models. In addition to showing whether there is a good correlation, it also partitions data into groups of low and high probability of response. The soil test value where this split occurs is known as the soil critical level. This fundamental separation recognizes the basic fact that a soil test cannot predict yield or the absolute amount of response. A soil test can only be used to determine the probability that a response will occur (Fitts, 1955; Fitts and Nelson, 1956; Dahnke and Olsen, 1990). Cate and Nelson (1971) also developed a simple statistical procedure for dividing soil test data into two classes.

When the Cate and Nelson method is used for analyzing greenhouse yield data, it can give a rough approximation of the critical soil test level (Dahnke and Olsen, 1990). When there are sufficient data to permit more separations, soil test data can be partitioned into three or more categories. If three categories are used, low, medium and high nutrient levels can be assigned to the levels where the probability of obtaining a fertilizer response is great, 50%, and small (Dahnke and Olsen, 1990). When using the Cate-Nelson procedure, both graphical and analysis of variance methods can be applied to establish three or more soil test classes (Nelson and Anderson, 1977). However, caution should be given to the analysis of variance method of Cate-Nelson since it is seriously flawed and should not be recommended.

Basic Cation Saturation Ratio Approach

The basic cation saturation ratio concept originated in New Jersey with Bear and his co-workers (Bear et al., 1945; Bear and Toth, 1948; Hunter, 1949; Hunter et al., 1943;

Prince et al., 1947). These papers proposed the basic cation saturation ratio (BCSR) concept which states that an optimum soil environment for plant growth is created when the cation exchange complex has an "ideal ratio" of 65, 10, 5, and 20% Ca, Mg, K, and H, respectively. Therefore, a Ca/Mg ratio of 6.5, on the equivalent basis (all Ca/Mg ratios mentioned below are on the equivalent basis), was proposed as the "ideal ratio". This "ideal ratio" was derived from 8 years of work with alfalfa on New Jersey soils. Later, Graham (1959) modified Bear's original ratio concept to a ratio range concept which states that crop growth and yield would be optimum when soil was saturated within the ranges of 65 to 85% Ca, 6 to 12% Mg, and 2 to 5% K and with H ions occupying the remaining sites. Therefore, the Ca/Mg ratio could range from 5 to 14.

The BCSR concept played a dominant role in shaping lime and fertilizer recommendations in the US (McLean and Brown, 1984). It is stated by Tisdale et al. (1985) that plant deficiencies of Mg can occur in soils with large ratios of exchangeable Ca/Mg and this ratio should ideally not be greater than 7 . In the new edition of this book (Tisdale et al., 1993), the authors modified the upper range of the critical level to 10 to 15. In Hawaii, a Ca/Mg ratio of 3 on the $cmol_c\ kg^{-1}$ basis (5 on the $mg\ kg^{-1}$ basis) was recommended for balance of soil exchangeable Ca and Mg in addition to supplying adequate levels of these two cations for three soil categories (Tamimi et al., 1994). To ensure Ca and Mg balance, the minimum and maximum desired Ca/Mg ratios were used for checking liming recommendations for tropical acid soils in the Fertilizer Advisory Consulting System computer program (Li et al., 1996).

The concept of cation ratio seems reasonable in the light of basic cation exchange phenomena and the effects that the degree of saturation of one cation may have on its availability and that of other cations (McLean, 1977). The "ideal" Ca/Mg ratio or ratio range possesses a certain appeal on theoretical grounds such as Ca and Mg balance and Ca and Mg antagonism. However, studies on the effects of varying soil Ca/Mg ratios on crop yield have generally failed to support the concept of an "ideal' ratio (Moser, 1933; Hunter, 1949; Bear and Toth, 1948; Giddens and Toth, 1951; Halstead et al., 1958; Adams and Henderson, 1962; MacLean and Finn, 1967; Martin and Page, 1969; McLean and Carbonell, 1972; Spies, 1974; Simson et al., 1979; Van Lierop et al., 1979; Eckert and McLean, 1981; McLean et al., 1983; Grant and Bailey, 1990; Franklin et al., 1991; Reid, 1996). It can be concluded from these studies that the soil Ca/Mg ratio could vary over a wide range for maximum crop yield. Therefore, the concept of an "ideal" Ca/Mg ratio or ratio range for liming and fertilizer recommendations appears to lack solid evidence. Eckert (1987) indicated that recommendations that were not cost effective often occurred when unnecessary additions of calcitic lime or relatively expensive Mg were recommended to alter the Ca/Mg ratio.

Some studies have found that yields were reduced by either Ca deficiency or Mg toxicity when soils have low Ca/Mg ratios (MacLean and Finn, 1967; Van Lierop et al., 1979; Souza and Ritchey,1988; Grant and Bailey, 1990). Therefore, critical levels of Ca/Mg ratio were found at lower Ca/Mg ratios in these studies. However, no study has found critical levels of Ca/Mg ratio for higher Ca/Mg ratios, above which yield reduction may occur due to Mg deficiency or Ca toxicity. Moreover, most of these studies on the relationship of the soil Ca/Mg ratio with crop yield were conducted in temperate regions.

Available information is limited for evaluating the "ideal" Ca/Mg ratio in tropical and subtropical areas where characteristics of acid soils are quite different from those of temperate areas.

Yield responses to soil Ca and Mg

Many researchers have reported that sufficient levels of soil Ca and Mg are essential for maximum crop yield. Kamprath (1984) indicated that a Ca level of 1.0 $cmol_c$ kg^{-1} (200 mg kg^{-1}) appears to be a minimum value for good growth of many plants in tropical soils. Melsted (1953) observed Ca deficiency symptoms on plants growing in soils having pH values below 4.5 and containing <400 mg Ca kg^{-1}(2 $cmol_c$ kg^{-1}). McLean (1982) reported that Ca deficiencies occurred in millet and alfalfa at about 3 $cmol_c$ kg^{-1} (600 mg kg^{-1}) in Ohio. The growth of tropical and temperate legume species, as influenced by Ca supply, was studied on a very sandy soil with pH 5.5 and having extremely low exchangeable Ca (Andrew and Norris, 1961). Maximum growth of most species was obtained at an exchangeable Ca content of 0.87 $cmol_c$ kg^{-1} (174 mg kg^{-1}). In Wisconsin (Haby et al., 1990), sufficient soil exchangeable Ca levels range from 250 mg kg^{-1} (1.25 $cmol_c$ kg^{-1}) in sandy soils to 500 mg kg^{-1} (3 $cmol_c$ kg^{-1}) in silty clay soils.

Adams (1984) pointed out that a deficiency of Mg occurred when soil exchangeable Mg was about 0.1 $cmol_c$ kg^{-1} (12 mg kg^{-1}) or less in the Ap horizon in the southern USA. McLean (1982) reported that Mg deficiencies occurred in millet and alfalfa at about 0.25 $cmol_c$ kg^{-1} (30 mg kg^{-1}) while earlier McLean and Carbonell (1972) reported that 0.58 $cmol_c$ kg^{-1} (70 mg kg^{-1}) of soil at pH 5.4 was inadequate for maximum yield of alfalfa. Fox and Piekielek (1984) reported that the exchangeable Mg level recommended for agronomic crops by different soil-testing services ranged from 25 to 180 mg kg^{-1}(0.21 to 1.5 $cmol_c$ kg^{-1}) Haby et al. (1990) pointed out that research on various crops and soils indicated a range of critical levels for soil exchangeable Mg that varied from 7 to 35 mg kg^{-1}(0.06 to 0.3 $cmol_c$ kg^{-1}) Furthermore, their survey indicated that the range of exchangeable Mg above which fertilizer is no longer recommended varied from 25 to 60 mg kg^{-1} (0.21 to 0.5 $cmol_c$ kg^{-1}) and this range varied from 30 mg kg^{-1} (0.25 $cmol_c$ kg^{-1}) for sandy soils to 50 mg kg^{-1} (0.42 $cmol_c$ kg^{-1}) for silts and clays and was highest (60 mg kg^{-1} or 0.5 $cmol_c$ kg^{-1}) in Piedmont soils (Haby et al., 1990). In the United Kingdom, guidelines established by the advisory workers (Doll and Lucas, 1973) agree fairly well with North American observations: deficiency symptoms generally occur in most field crops, vegetables, fruit, and glasshouse crops when soil Mg <25 mg kg^{-1} (0.21 $cmol_c$ kg^{-1}) and deficiency symptoms are expected in sugarbeet, potato, Kale, fruit, and glasshouse crops when soil Mg is 25 to 50 mg kg^{-1}(0.21 to 0.42 $cmol_c$ kg^{-1}).

Although sufficient soil Ca or Mg levels at which crops are no longer expected to respond to Ca or Mg application varied among laboratories and soil types, it was found that the range of Ca sufficiency levels is 200 mg kg^{-1} to 600 mg kg^{-1} (1 to 3 $cmol_c$ kg^{-1}) and the range of Mg sufficiency levels is 7 mg kg^{-1} to 70 mg kg^{-1} (0.06 to 0.6 $cmol_c$ kg^{-1}) in the United States. In Hawaii (Tamimi et al., 1994), however, sufficient soil exchangeable Ca is believed to be 1500-2000 mg kg^{-1} (7.5 to 10 $cmol_c$ kg^{-1}) for heavy soils with bulk density close to 1.0 g cm^{-3} and 3000-4000 mg kg^{-1} (15 to 20 $cmol_c$ kg^{-1}) for light soils with bulk density close to 0.5 g cm^{-3}. Also, in Hawaii, soil Mg sufficiency levels are believed to be 300-400 and 600-800 mg kg^{-1} (2.5 to 3.3 and 5 to 6.7 $cmol_c$ kg^{-1}) for heavy and light soils, respectively (Tamimi et al., 1994). The sufficient Ca level for heavy soils has been updated recently (Yost, 1999) to 1000-15000 mg kg^{-1}(8.3 to 7.5 $cmol_c$ kg^{-1}). It is obvious that the Hawaii sufficiency levels of soil Ca and Mg are much higher than those of the rest of the USA.

The differences of crop tolerance to low soil Ca and Mg levels have been recognized by agronomists. Calcium deficiencies in the field are usually related to specific crops, which have specific internal problems with delivering Ca to certain tissues. Such crops suffer Ca deficiencies on the same soil that supplies adequate Ca for other crops (Adams, 1984). Such crops in the southern USA are peanut (Cox et al., 1982), tomato (Geraldson, 1957), tobacco (Peedin and McCants, 1977), and celery (Geraldson, 1954). Magnesium deficiencies also most commonly occur in crops such as tobacco, citrus, potato, cotton, and soybean (Adams, 1984). Moreover, Ca or Mg is most likely to be deficient in vegetables grown on sandy acid soils in areas of moderate to high rainfall or when large amounts of Ca or Mg based lime or K fertilizer have been applied. This applies specifically for Ca and Mg sensitive vegetable crops such as carrots, celery, tomatoes, and spinach (Swiader et al., 1992; von Uexkull, 1986; and Adams, 1984).

The critical or sufficiency levels of soil exchangeable Ca and Mg varied greatly with soil types, regional growing conditions and crops. It is often necessary to carry out correlation and calibration studies locally to establish satisfactory soil critical or sufficiency levels of soil Ca and Mg. Even considering those factors, the Ca/Mg ratio before and after liming and fertilizing may further affect Ca and Mg availability for plants.

Most researchers who studied yield responses to Ca/Mg ratios concluded that once adequate levels of soil Ca and Mg were presented, the Ca/Mg ratio had relatively little effect on crop yield. However, many acid soils in the tropics and subtropics have very low amounts of exchangeable Ca and a low Ca saturation of the effective cation exchange capacity (ECEC) (Kamprath, 1984). Exchangeable Mg is also very low in these acid soils. The author reviewed 102 Hawaii soils described in the Soil Survey of Hawaii conducted in the 1950s and 1960s (Soil Conservation Service, 1976). It was interesting to find out that acid soils with pH<6 had low average soil exchangeable Ca, 3.57 $cmol_c\ kg^{-1}$ (714 $mg\ kg^{-1}$) and Mg, 2.01 $cmol_c\ kg^{-1}$ (241 $mg\ kg^{-1}$) levels. Near neutral or alkaline soils with pH>6, on the other hand, had high average soil Ca, 15.14 $cmol_c\ kg^{-1}$ (3028 $mg\ kg^{-1}$) and Mg, 7.49 $cmol_c\ kg^{-1}$ (899 $mg\ kg^{-1}$). Therefore, Ca and Mg level as well as the Ca/Mg ratio in tropical and subtropical acid soils may play important roles in determining Ca and Mg nutrition and crop yield.

Ca and Mg antagonism

Most liming materials are Ca-based and excess Ca can induce Mg deficiency. In a number of field trails in Alabama, liming with a high grade calcitic material caused Mg deficiency where none existed before liming (Adams, 1975). More evidence of substantial reductions in exchangeable Mg with liming were obtained by Sumner et al. (1978); Sims and Ellis (1983); Farina et al. (1980); Chan et al. (1979); Grove and Sumner (1985); and Myers et al. (1988). Sumner et al. (1978) and Grove and Sumner (1985) suggested that limited Mg availability may be a contributing factor in yield reductions commonly observed when acid soils are limed to near neutrality.

On the other hand, using Mg-based lime may induce Ca deficiency or cause Mg toxicity. On an acid Brazilian Oxisol, liming with $MgCO_3$ resulted in less than 100 kg ha^{-1} in soybean grain yield while liming with $CaCO_3$ produced an average yield of 2100 kg ha^{-1} (Souza and Ritchey, 1988). The authors suggested that when $MgCO_3$ was applied, excessive soil Mg in relation to soil Ca resulted in a Ca/Mg ratio less than 1.0, which caused the low yields. Calcium deficiency of barley was also reported when a Latosol of South China was over-limed with $MgCO_3$ (Gong, et al., 1981).. Calcium deficiencies or Mg toxicities have also been alleged to occur in Wisconsin soils that have been limed to near-neutral pH with dolomitic limestone, which is readily available in that area (Simson et al., 1979). Eckert and McLean (1981) were able to create Mg-induced Ca deficiency in German millet and alfalfa with Mg saturation near 15% at pH 5.

To reduce the likelihood of such an occurrence in actual production situations, proper liming programs should consider Ca and Mg balance by avoiding very high or very low Ca/Mg ratios after liming.

Yield responses to the soil Ca/Mg ratio or ratio range

Early studies on crop responses to the soil Ca/Mg ratio were conducted mainly in the temperate region of the US. Hunter (1949) found no ideal Ca/Mg ratio for alfalfa in the range of 0.24 to 32. Giddens and Toth (1951) found no effects of varying soil cation ratios on the growth of white clover as long as Ca^{2+} was the dominant ion on the exchange complex. McLean and Carbonell (1972) showed no effect of varying soil Ca/Mg ratios on yields of alfalfa or German millet. Simson et al. (1979) conducted field trials at four sites in Wisconsin and found that Ca/Mg ratios ranging from 0.8 to 5.0 had no effect on corn or alfalfa yields. Greenhouse studies with Ca/Mg ratios that ranged from 0.4 to 30 (Bear and

Toth, 1948; Martin and Page, 1969; Adams and Henderson, 1962; McLean and Carbonell, 1972) and field experiments with Ca/Mg ratios of 1 to 4.5 (Moser, 1933) and 0.6 to 20 (Spies, 1974) concluded that there was a wide range of Ca/Mg ratios in which no yield reduction was observed. Simson et al. (1979) believed that if soil pH is near neutral and sufficient quantities of K, Ca, and Mg are present, the Ca/Mg ratio is not a yield limiting factor. In Canada, Halstead et al (1958) found no significant relationship between exchangeable Ca/Mg ratios in the range of 1 to 13.5 and crop yields. Later, however, MacLean and Finn (1967) suggested that yield was lowered by an exchangeable Ca/Mg ratio of 0.62. Also, a growth chamber study with onion on three Histosols with soil Ca/Mg ratios ranging from 0.05 to 16 in Quebec, Canada (Van Lierop et al., 1979) showed that although an upper critical Ca/Mg ratio was not found, yield decreased rapidly as the extractable soil Ca/Mg ratio became smaller than the lower critical ratio of 0.5.

More systematic studies were carried out in Ohio to investigate the validity of an "ideal" ratio for maximum crop yield (Eckert and McLean, 1981; McLean et al., 1983). Study in a growth chamber using a Loudonville silt loam of Ohio with Ca/Mg ratios ranging from 1.3 to 53 (Eckert and McLean, 1981) showed that maximum yields of German millet and alfalfa were noted at soil Ca/Mg ratios of 3 to 11, however, lower yields were also found within this range. Later, a similar result was obtained from a field experiment over a period of six cropping years with the cropping sequence of corn, corn, soybean, wheat, alfalfa and alfalfa. The highest five and the lowest five yields overlapped in six crops on an average Ca/Mg ratio range of 2.3 to 26.8 (McLean et al., 1983). Mengel (Agronomy Crops and Soils Notes no.376, Purdue Univ.) found that Mg deficiencies in Indiana occurred largely on sandy, low CEC soils. It was noted that once an adequate amount of exchangeable Mg was present on the exchange complex, the ratio of Ca/Mg can be anywhere in the range of 1 to 49 without affecting crop yields. More recently, Grant and Bailey (1990) in Canada conducted a growth chamber experiment with Ca/Mg ratios ranging from 0.77 to 9.14 on two Orthic black Chernozemic soils with high soil Ca and Mg levels. They found that Ca/Mg ratios of 0.77 and 1.23 resulted from 12.6 $cmol_c\ kg^{-1}$ (1512 $mg\ kg^{-1}$) Mg application on soils with 994 and 708 $mg\ kg^{-1}$ (4.97 and 5.90 $cmol_c\ kg^{-1}$) exchangeable soil Mg, respectively, caused yield reduction in flax. Two more studies conducted in temperate regions of the US also supported the early findings reviewed above. Franklin et al. (1991) in a greenhouse study on the effect of excessive Mg in irrigation water on wheat and corn growth showed that Ca/Mg ratios in soil leachate that ranged from 0.3 to 1.6 did not reduce grain yield but Ca/Mg ratios that ranged from 0.04 to 0.16 caused serious grain yield reduction. Reid (1996) applied liming material with Ca/Mg ratios that ranged from 1 to 267 on a soil with low soil Ca and Mg levels for alfalfa and birdsfoot trefoil. No significant influence of Ca/Mg ratios in liming material on yields of either species was found.

Simson et al. (1979) reviewed the results of Ca/Mg ratio experiments reported in the literature and schematically summarized greenhouse studies and field experiments with Ca/Mg ratios that ranged from 0.4 to 30 and concluded that there was a wide range of Ca/Mg ratios in which no yield depression was observed. They proposed a relationship between Ca/Mg ratios and yields (Figure 2-1). The curve shown represents a boundary line which includes all data points in which no yield decrease was observed from greenhouse and field studies. Only at extremely low and high Ca/Mg ratios do yield reductions occur. The critical levels of Ca/Mg ratio are around 0.5 for lower and 30 for higher Ca/Mg ratios, respectively. At lower Ca/Mg ratios, yields might be reduced by Ca deficiency, Mg toxicity or Ca and Mg nutritional imbalance, whereas at higher ratios the reverse might be true. Some later studies (Grant and Bailey, 1990; Franklin et al., 1991; Souza and Ritchey, 1988) confirmed the yield reduction caused by lower Ca/Mg ratios and suggested the critical levels in the lower ratio range. However, no study has shown

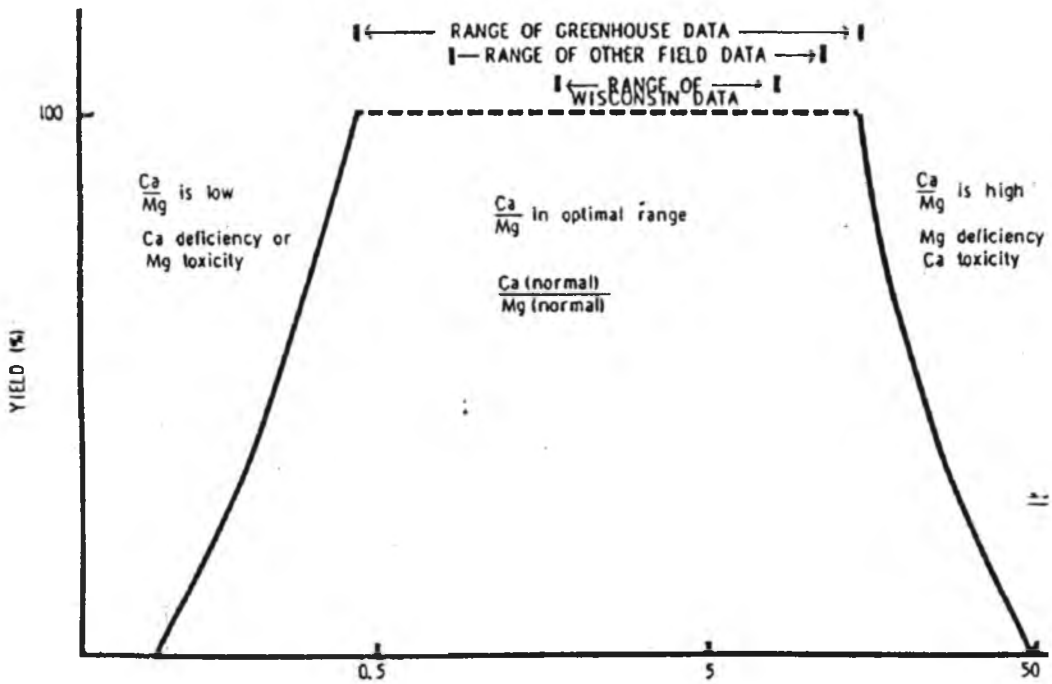

Figure2-1. Range in Ca/Mg ratios over which no yield depression due to that factor has been observed
Source: Simson et al. (1979)

yield reduction from very high Ca/Mg ratios and therefore, no critical level of Ca/Mg ratio for the higher ratios can be established. Since Simson et al (1979) had no data on Ca/Mg ratios above 30, they appear to have no basis for assuming yield declines at or above 30.

Ca/Mg ratios in tropical and subtropical soils

Information in the literature on tropical and subtropical soils is limited. The previously mentioned study in Brazil showed that a Ca/Mg ratio less than 1.0 caused serious reduction of soybean yield (Souza and Ritchey, 1988). In a study in Western Samoa, yield of sweet corn increased when Ca/Mg ratio increased from 1.5 to 5.5 upon liming but there was no change when the ratio increased further from 5.5 to 11.5 (Hunter et al., 1995).

Ca/Mg ratios in tropical and subtropical soils may vary widely due to the range of different parent materials from which the soil developed. The Ca/Mg ratios in the topsoils of some important soils in subtropical regions of China varied from 1.16 in basalt ferric red earth to 27.35 in limestone paddy soil (Gong, 1981). Ca/Mg ratios also differ with soil fertility. In the Brazilian Cerrado, the least productive vegetation group ""cerrados" was characterized by Ca/Mg ratios <1.0 while forest vegetation was characterized by ratios of 3.0 or greater (Cochrane, 1989).

In Hawaii, the author reviewed the Soil Survey of Hawaii conducted in the 1950s and 1960s (Soil Conservation Service, 1976) and found that the soil Ca/Mg ratios ranged from 0.01 to 30 in the top soil layers of 102 soil profiles. Although there is little difference in the average Ca/Mg ratio of 2.4 for the acid soils (pH<6), and 2.6 for the near neutral or alkaline soils (pH=/>6), acid soils have great variability in the Ca/Mg ratio with a CV of 164% compared to a CV of 70% for neutral or alkaline soils. Similar to the results found with pH, the average Ca/Mg ratios for both the higher fertility soils (cultivated land) and the lower fertility soils (uncultivated land) were 2.5. However, the ratios in the cultivated soils were more clustered with a CV of 95% compared to a CV of 142% for the uncultivated soils. The greater Ca/Mg ratio range in acid soils and low fertility soils suggests that there is a greater possibility of Ca/Mg imbalance in these soils.

Liming (soil pH) effect

Most researchers who studied yield responses to the Ca/Mg ratio in temperate areas also concluded that the Ca/Mg ratio had little effect on crop yield when acidity was neutralized. This may be true for temperate soils but may be not true for tropical and subtropical soils. Soils in the humid tropics in their natural state are generally acid with pH<5 (Pearson, 1975) and must be limed to increase productivity. Liming acid soils to pH 6.5 to 7 is the common practice in the temperate zone (Thomas and Hargrove, 1984). However, in tropical and subtropical acid soils, particularly in Oxisols and Ultisols, it appears to be unnecessary to lime soil to pH 7 which can result in yield reduction (Farina et al., 1980). Many early studies in tropical and subtropical areas followed the practice used on highly productive Mollisols and Alfisols in temperate regions. However, when tropical and subtropical soils were limed to near neutrality, yield decreases often resulted (Kamprath, 1984). Similar to the reactions to liming, the Ca/Mg ratio may have different behaviors on temperate and tropical soils.

The yield reduction resulting from over-liming acid tropical soils was caused largely by nutritional imbalance. The ECECs of highly weathered soils in the tropics and subtropics are quite low (Kamprath, 1984), which results in weak buffer capacity for cations. These soils also contain small amounts of Ca and Mg so that Ca and Mg imbalances can readily occur as a result of heavy liming.

The Mg ion is more highly hydrated than the Ca ion and its larger hydrated size makes it weakly bonded and gives it a greater tendency to be adsorbed on pH-dependent sites. Therefore, there is a greater percentage of Mg in solution which increases the possibility of Mg leaching. Moreover, more Mg than Ca can be trapped in nonexchangeable form when highly weathered soils are limed and this reduces Mg availability (McLean and Brown, 1984). The phenomena of more Mg being in solution and fixed in nonexchangeable form can lead to more Mg deficiencies than Ca deficiencies in tropical and subtropical soils where the CEC is dominated by pH-dependent or variable charges.

Reduction in exchangeable Mg with liming, sometimes referred to as Mg "fixation" has also been reported in many types of soils but most frequently in highly weathered Ultisols and Oxisols (Pavan et al., 1984). It has been suggested that Mg fixation is directly related to exchangeable Al in the soil (Grove et al., 1981; Farina et al., 1980; Grove and Sumner, 1985). Myers et al. (1988) observed that the reduction in exchangeable Mg was positively correlated with exchangeable, organically chelated, and poorly crystallized inorganic Al. Exchangeable Al, however, produced the best correlation with the reduction in Mg, which supports the hypothesis that Mg "fixation" is due to the occlusion or coprecipitation of Mg with Al upon liming.

Co-Variation of Cations

Few studies regarding cations have considered the fact that the composition of cations on exchange sites changes when fertilizer cations are added which can affect crop response to a particular cation. Since a soil has a specific Effective Cation Exchange Capacity, addition of fertilizer cations displaces some soil cations from the exchange complex and changes the ion composition. For example, if increasing amounts of K are added to a soil with a constant amount of Ca and then the system is leached, the amount of Ca remaining on exchange sites will decrease as the amount of K added increases. This results in a differential of Ca as well as K in the final system. Therefore, the results of crop response to K in this system must be interpreted with caution because Ca varies with K.

CHAPTER 3

EXPERIMENTAL PLAN AND PROCEDURES

Soil

An acid Hawaii Ultisol (Manana Series --a fine, parasesquic, semiactive, isolyperthermic Ustic Palehumults) was selected for this study. The soil was collected from the Waiawa Correctional Facility in central Oahu at an elevation of about 250 m, with a mean annual rainfall of 1500 mm, an annual minimum temperature of 20 °C and an annual maximum temperature of 23 °C (Dept. of Agronomy and Soil Science, 1993).The soil collection site was in an uncultivated area with grass. After the vegetation and the top 5 cm of soil were removed, the bulk soil samples were collected from the 5 cm to 20 cm depth. The soil was ground to pass a 6-mm sieve and air-dried in the greenhouse. The soil is characterized as having low soil pH, and low exchangeable soil Ca and Mg levels. The soil chemical properties are shown in Table 3-1.

Table 3-1. Chemical properties of the Manana soil series

Property	Value
pH (1:1 H_2O)	4.35
pH (1:1 KCl)	3.90
Exchangeable Ca ($cmol_c\ kg^{-1}$)	0.565
Exchangeable Mg ($cmol_c\ kg^{-1}$)	0.667
Exchangeable Na ($cmol_c\ kg^{-1}$)	0.830
Exchangeable K ($cmol_c\ kg^{-1}$)	0.148
CEC ($cmol_c\ kg^{-1}$)	21.07
ECEC ($cmol_c\ kg^{-1}$)	2.812
Exchangeable Al ($cmol_c\ kg^{-1}$)	1.544
Available P ($mg\ kg^{-1}$)	2.7
Organic C (%)	4.62
Total N (%)	0.30

Experimental design

Two pot experiments, a Ca experiment and a Mg experiment, were conducted in the greenhouse. Seven levels of Ca or Mg were used in each experiment in order to produce a wide range of soil Ca and Mg levels. Two kilograms of air-dried soil was placed in each pot and lettuce (*Lactuca sativa* L.), Manoa variety was selected as the test crop for both experiments since lettuce is the one of major vegetable crops grown in Hawaii. Each experiment was replicated 3 times and arranged in a randomized complete block design.

Soil pH was adjusted to 6 with $Ca(OH)_2$ in the Mg experiment and with $Mg(OH)_2$ in the Ca experiment. This brought the soil in both experiments to the desired pH and supplied the experiments with a uniform amount of Ca and Mg. This also limited non-treatment sources of Ca and Mg. Soil pH 6 is the minimum soil pH for lettuce. The amount of $CaCO_3$ required to rise soil pH to 6 was calculated based on a lime titration curve in the Hawaii Soil Fertility Manual (Silva, 1997) and then the amount of $Ca(OH)_2$ and $Mg(OH)_2$ were calculated based on their neutralizing values. The Ca levels were established with $CaSO_4$ in the Ca experiment and Mg levels were established with $MgSO_4$ in the Mg experiment. The treatment design for the Ca experiment is shown in Table 3-2 and the treatment design for the Mg experiment is shown in Table 3-3. High rates of Ca and Mg application were needed in order to obtain the highest treatment levels of Ca and Mg which were close to the current recommended soil Ca and Mg sufficiency levels.

After the lime, Ca, and Mg treatments were applied, the soil in the pot was brought to field capacity and allowed to equilibrate for 17 days in order to obtain stable soil pH and exchangeable cation levels. Since high amounts of salts in the forms of

Table 3-2. Treatment design for the Ca experiment

Treatment	$Ca(OH)_2$	$CaSO_4$	$Mg(OH)_2$	$MgSO_4$
	(Ca kg ha^{-1})		(Mg kg ha^{-1})	
1	0	0	1200	0
2	0	1000	1200	0
3	0	2000	1200	0
4	0	3000	1200	0
5	0	4000	1200	0
6	0	5000	1200	0
7	0	6000	1200	0

Table 3-3. Treatment design for the Mg experiment

Treatment	$Ca(OH)_2$	$CaSO_4$	$Mg(OH)_2$	$MgSO_4$
	(Ca kg ha^{-1})		(Mg kg ha^{-1})	
1	2000	0	0	0
2	2000	0	0	250
3	2000	0	0	500
4	2000	0	0	750
5	2000	0	0	1000
6	2000	0	0	1250
7	2000	0	0	1500

$CaSO_4$ and $MgSO_4$ had been added to the soil in most treatments, soil electrical conductivity ranged from 0.7 to 9.5 dS m^{-1} (Appendix B) indicated that salinity levels in many treatments were too high (higher than 3 dS m^{-1}) to allow normal lettuce growth. Salt effects can be a confounding factor affecting the treatments. Moreover, high amounts of Ca and Mg in the soil solution can create an environment that is different from the soil environment desired in which Ca and Mg are predominantly exchangeable cations. Leaching also simulates field conditions in which rain or irrigation can leach applied lime and fertilizers. Therefore, the soil was leached to eliminate the salt effect and attain soil conditions that were close to a field environment. Each pot was leached 5 times with 1 liter of de-ionized water each time at 12 hour intervals. After leaching, soil conductivities of all treatments were at normal levels and ranged from 0.6 to 2.9 dS m^{-1} (Appendix B). The actual levels of exchangeable Ca and Mg in each pot were determined, and the Ca/Mg ratios on the $cmol_c\ kg^{-1}$ basis were calculated (Tables 3-4 and 3-5). The levels of soil Ca obtained were 0.57 to 8 $cmol_c\ kg^{-1}$ and levels of soil Mg were 0.67 to 3.3 $cmol_c\ kg^{-1}$.

Table 3-4. Average Ca and Mg levels for the Ca experiment after leaching

Treatment	Soil Ca ($Ca\ cmol_c\ kg^{-1}$)				Soil Mg ($Mg\ cmol_c\ kg^{-1}$)				Ca/Mg ($cmol_c\ kg^{-1}$ basis)			
	1	2	3	Avg	1	2	3	Avg	1	2	3	Avg
1	0.577	0.543	0.572	0.565	5.230	4.470	3.787	4.492	0.11	0.12	0.15	0.13
2	1.856	1.893	2.002	1.915	3.443	3.657	3.763	3.625	0.54	0.52	0.53	0.53
3	4.286	2.460	3.930	3.560	3.470	2.436	3.680	3.192	1.24	1.01	1.07	1.11
4	3.760	3.650	4.020	3.810	2.173	2.316	2.456	2.317	1.73	1.58	1.64	1.65
5	5.902	4.942	4.264	5.035	2.173	1.983	2.082	2.075	2.72	2.49	2.05	2.42
6	5.668	5.324	5.542	5.510	1.883	2.083	2.242	2.067	3.01	2.56	2.47	2.66
7	7.758	6.018	7.704	7.160	1.117	1.211	1.543	1.292	6.94	4.97	4.99	5.55

Procedure for greenhouse experiments

The blanket fertilizers (NPK) were based on the original soil analysis and the fertilizer recommendations in the Hawaii Soil Fertility Manual (Silva, 1997). The amounts of N, P and K were 140, 600 and 140 kg ha^{-1}, respectively, applied as $(NH_4)_2HPO_4$, KH_2

PO_4 and $NaH_2PO_4 \cdot H_2O$. The fertilizer rates were converted from kg ha^{-1} to g pot^{-1} by a conversion factor of 1/1000 (assuming a 2,000,000 kg furrow slice of soil per ha). Blanket fertilizers were applied to the soil and mixed thoroughly before the lettuce was transplanted.

Table 3-5. Average Ca and Mg levels for the Mg experiment after leaching

Treatment	Soil Ca ($Ca\ cmol_c\ kg^{-1}$)				Soil Mg ($Mg\ cmol_c\ kg^{-1}$)				Ca/Mg ($cmol_c\ kg^{-1}$ basis)			
	1	2	3	Avg	1	2	3	Avg	1	2	3	Avg
1	4.784	4.823	4.722	4.780	0.622	0.729	0.642	0.667	7.7	6.62	7.35	7.19
2	3.966	3.592	4.900	4.155	1.400	1.395	1.499	1.433	2.82	2.58	3.27	2.90
3	3.894	4.234	3.892	4.005	2.056	2.100	2.100	2.083	1.89	2.02	1.85	1.92
4	3.312	3.920	3.822	3.685	2.555	2.518	2.513	2.525	1.30	1.56	1.52	1.46
5	4.438	3.904	3.156	3.835	3.483	3.160	2.821	3.158	1.27	1.24	1.12	1.21
6	3.874	3.568	3.696	3.715	3.940	2.858	3.263	3.350	0.98	1.25	1.13	1.11
7	3.408	3.336	3.526	3.425	3.220	2.984	3.290	3.167	1.06	1.12	1.07	1.08

Lettuce (Manoa variety) seeds were sown in unfertilized Manana soil and grown for three weeks. Afterward, 6 and 5 uniform seedlings were transplanted into each pot for the Ca and Mg experiment, respectively. The soil in the pots was kept at field capacity by adding the desired amount of de-ionized water daily.

The crop was harvested 5 weeks after transplanting. At harvest, the plants were cut at the soil surface. The above-ground portion of the plants in each pot was collected for biomass determination and nutrient analysis.

Measurements

The initial soil was analyzed for pH (1:1 H_2O), pH (1:1 KCl), organic carbon (a modified version of the Walkley-Black method), total N (the micro-Kjeldahl method), available P (the modified Truog method), exchangeable K, Ca, Mg and Na (1M Ammonium acetate at pH 7.0) and exchangeable Al (1 *M* KCl with soil:solution at1:10) according to the methods described in Hawaii Soil Fertility Manual (Silva, 1997) and by Page et al., (1982). The initial soil was also analyzed for CEC (1M Ammonium acetate at pH 7.0 method) described by Hendershot et al. (1993), and Effective CEC (sum of KCl exchangeable acidity and cations with K being measured separately) described by Baize (1993). Soil samples from each treatment before leaching were analyzed for pH (1:1 H_2O) and soil electrical conductivity (Jones, 1989). Soil samples from each treatment after leaching but before transplanting were analyzed for pH (1:1 H_2O), soil electrical conductivity (Jones, 1989) and exchangeable K, Ca, Mg and Na.

The fresh and dry weights of the above-ground portion of the plants in each pot were also determined. The above-ground portion of the plants for each pot was analyzed for Ca, Mg, P and K by the dry ashing method described by Jones (1989).

Statistical analysis

The experimental data were analyzed by the analysis of variance (AONVA) technique using the software Statistix 3.5 (Analytical Software, 1991) and the regression technique using the software TableCurve 3.10 (Jandel Scientific, 1991).

CHAPTER 4

RESULTS AND DISCUSSION

Yield Response to Soil Ca, Mg and the Ca/Mg ratio

Yield response to soil Ca

The response of lettuce to different soil Ca levels is shown in Figure 4-1 which indicates that lettuce made almost no growth and produced a very small amount of dry matter with the zero Ca treatment. The original soil Ca level was 0.57 $cmol_c\ kg^{-1}$. Application of 1000 kg ha^{-1} $CaSO_4$ increased soil Ca to about 1.92 $cmol_c\ kg^{-1}$ which resulted in normal growth of lettuce and produced much greater dry matter than the zero Ca treatment. A yield response curve was fitted by a ratio function:

$$Y=0.2355-0.07156/X^2 \ (r^2 = 0.659, P<0.001, n=21) \quad \ldots\ldots\ldots\ldots \quad [1]$$

where Y is yield (dry matter) and X is soil Ca. Therefore, poor growth of lettuce with the zero Ca treatment is clearly shown in Figure 4-2 while normal growth is demonstrated with the other Ca treatments.

Analysis of variance (Table 4-1) indicates that there was a significant effect of Ca treatments (P greater than 0.01) on lettuce yield. The means of Ca treatments are listed in Table 4-2 for overall comparison between treatments.

In the literature, adequate soil Ca ranged from 1 to 3 $cmol_c\ kg^{-1}$ (Kamprath, 1984; Melsted, 1953; McLean, 1982; Andrew & Norris, 1961; Haby et al., 1990). Therefore, in this study, lettuce was expected to respond to Ca applications because soil Ca was only 0.57 $cmol_c\ kg^{-1}$. It should be pointed out that there was a gradient of soil Mg levels in the

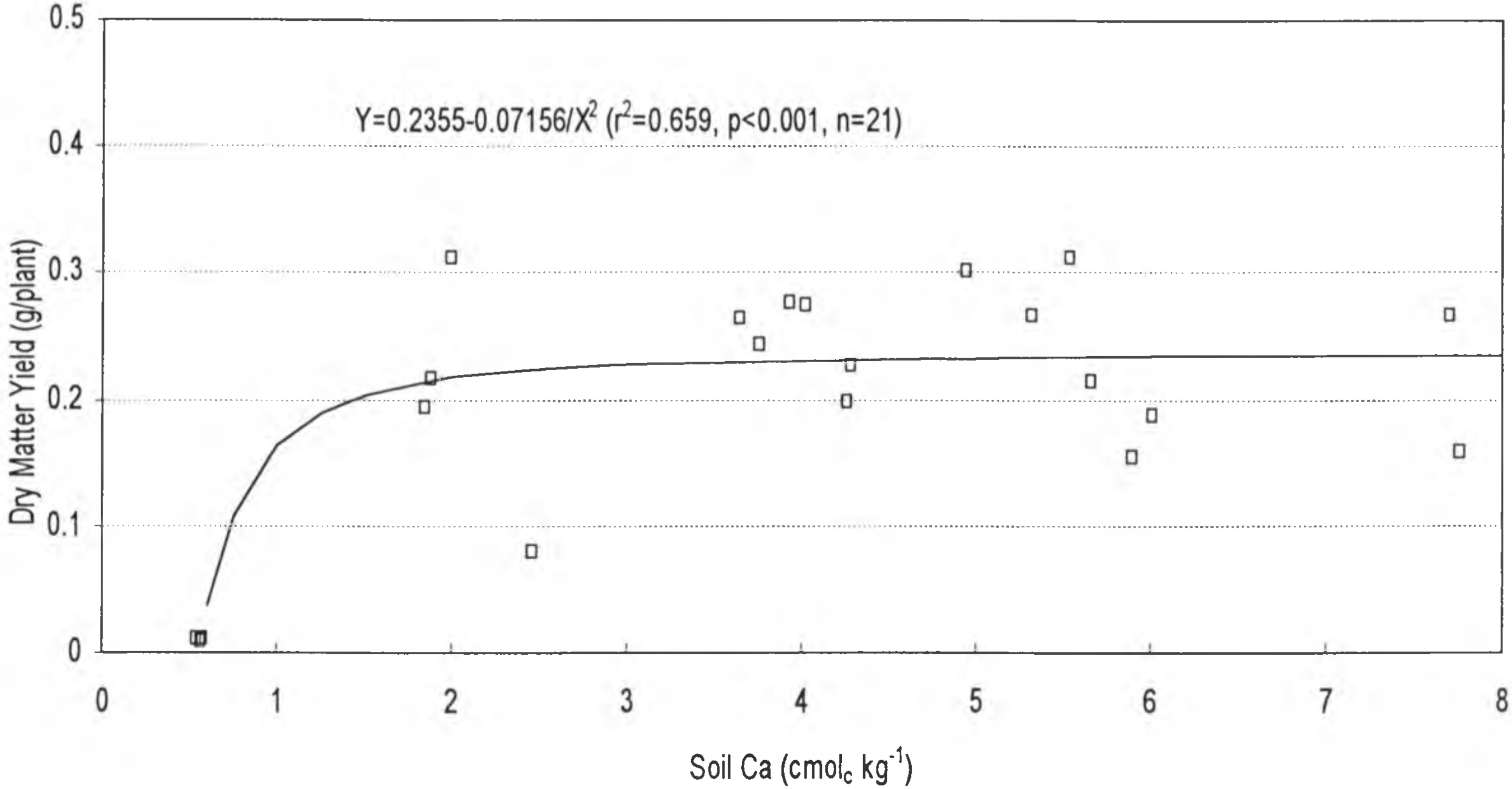

Figure 4-1. Yield Response of lettuce to soil Ca in the Manana soil series

Ca: kg ha^{-1}	0	1000	2000	3000	4000	5000	6000
Soil Ca cmol$_c$ kg^{-1}	0.57	1.92	3.56	3.81	5.04	5.51	7.16

Figure 4-2. Lettuce growth on different exchangeable soil Ca levels resulting from Ca treatments

Table 4-1. Analysis of Variance for Lettuce Yields with Ca Treatments

Source	DF	SS	MS	F	P
Ca treatment	6	0.13716	0.02286	7.54	0.0016
Replication	2	0.01522	0.00761	2.51	0.1229
Error	12	0.03639	0.00303		
Total	20	0.18877			

Table 4-2. Comparison of Mean Yields of Lettuce with Ca Treatments

Ca Treatments (Kg ha^{-1})	Mean (g $plant^{-1}$)
0	0.009
1000	0.235
2000	0.194
3000	0.260
4000	0.217
5000	0.263
6000	0.203

Ca experiment due to soil leaching and the variation of Mg levels was a co-varying factor with soil Ca, which may affect crop response to soil Ca. However, the soil Mg levels were all well within the adequate range and the effect of soil Mg on lettuce growth in this soil was found to be insignificant. Figure 4-3 shows that the main effect of soil Ca was not affected by soil Mg. Stepwise regression using soil Ca, Mg and the Ca/Mg ratio as independent variables shows that both Ca and the Ca/Mg ratio had significant effects on dry matter yield (P=0.001 and 0.006, respectively) and were included in the multiple

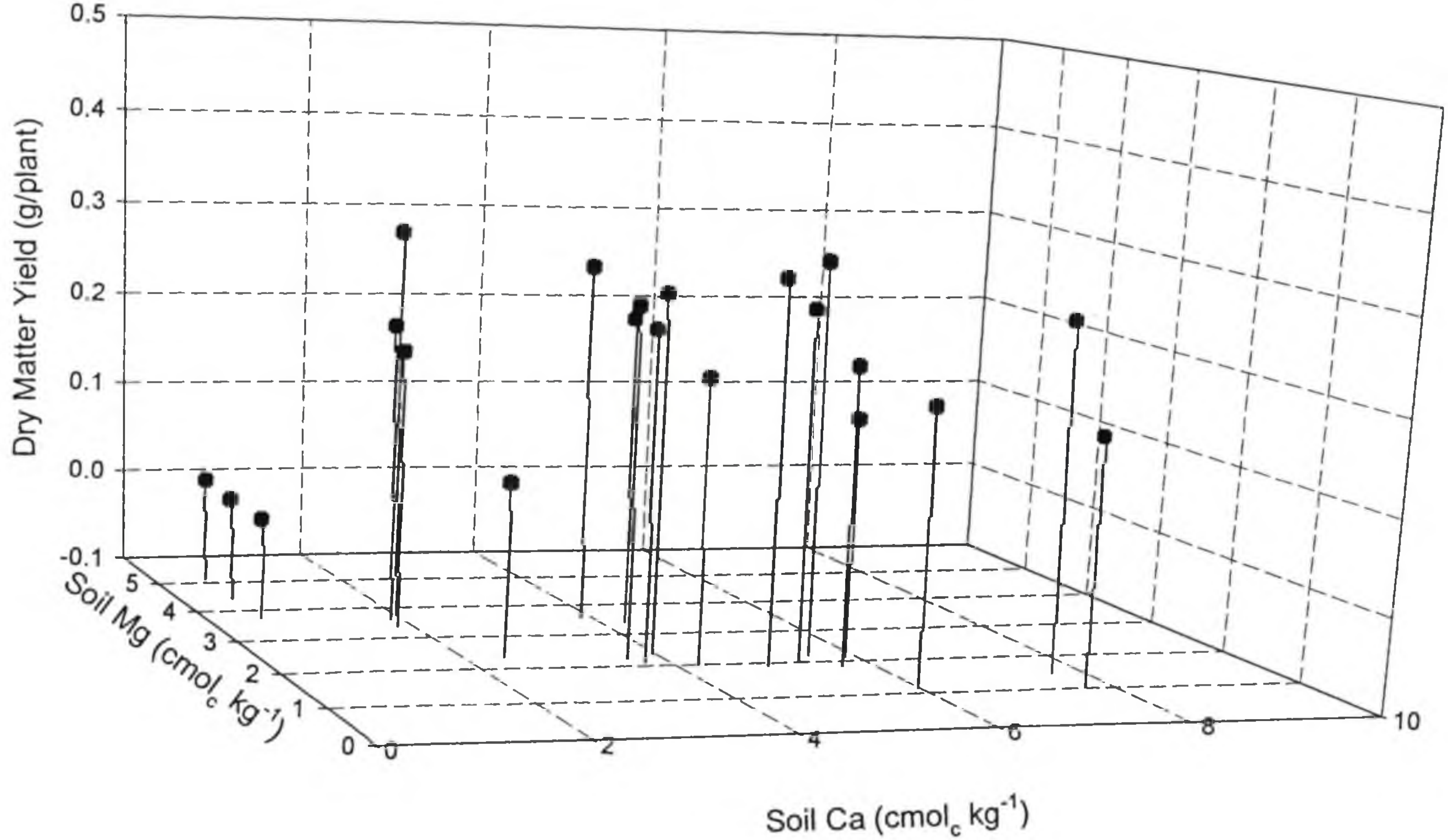

Figure 4-3 Lettuce Response to Soil Ca and Mg in the Ca Experiment

regression model but Mg did not significantly affect the yield (P=0.479) and was not included in the model (Appendix E). Therefore, soil Ca was the main factor causing the yield response although the soil Ca/Mg ratio also had some effect on yield.

Yield response to soil Mg

Lettuce growth did not increase as soil Mg increased from the original level of 0.67 $cmol_c\ kg^{-1}$ to over 3.5 $cmol_c\ kg^{-1}$. The scatter diagram of lettuce dry matter yield vs soil Mg in Figure 4-4 shows the data points are scattered randomly with no pattern of yield response. The growth of lettuce was normal with all soil Mg levels (Figure 4-5). Analysis of variance (Table 4-3) indicates that there was no significant effect (P less than 0.05) of Mg treatments on lettuce yield. The means of Mg treatments are listed in Table 4-4 for overall comparison of Mg treatments.

In the literature, the sufficient soil Mg level varied from 0.06 to 0.6 $cmol_c\ kg^{-1}$ (Adams, 1984; McLean, 1982; McLean & Carbonell, 1972; Fox and Piekielek, 1984; Haby et al., 1990). Therefore, in this study with soil Mg of 0.67 $cmol_c\ kg^{-1}$, it was less likely for lettuce to respond to Mg application. The results of this study, however, indicate that a soil Mg level of 0.67 $cmol_c\ kg^{-1}$ is at least adequate for lettuce growth. Further studies on soils with lower Mg levels are needed to more accurately identify the critical level for soil Mg in Hawaii. It should be pointed out that there was a gradient of soil Ca levels in the Mg experiment due to soil leaching and the variation of Ca levels was a co-varying factor which may affect crop response to soil Mg. However, since the soil Ca levels were all well within the adequate range, the effect is not likely to be significant enough to confound the response of lettuce to soil Mg. Stepwise regression using soil

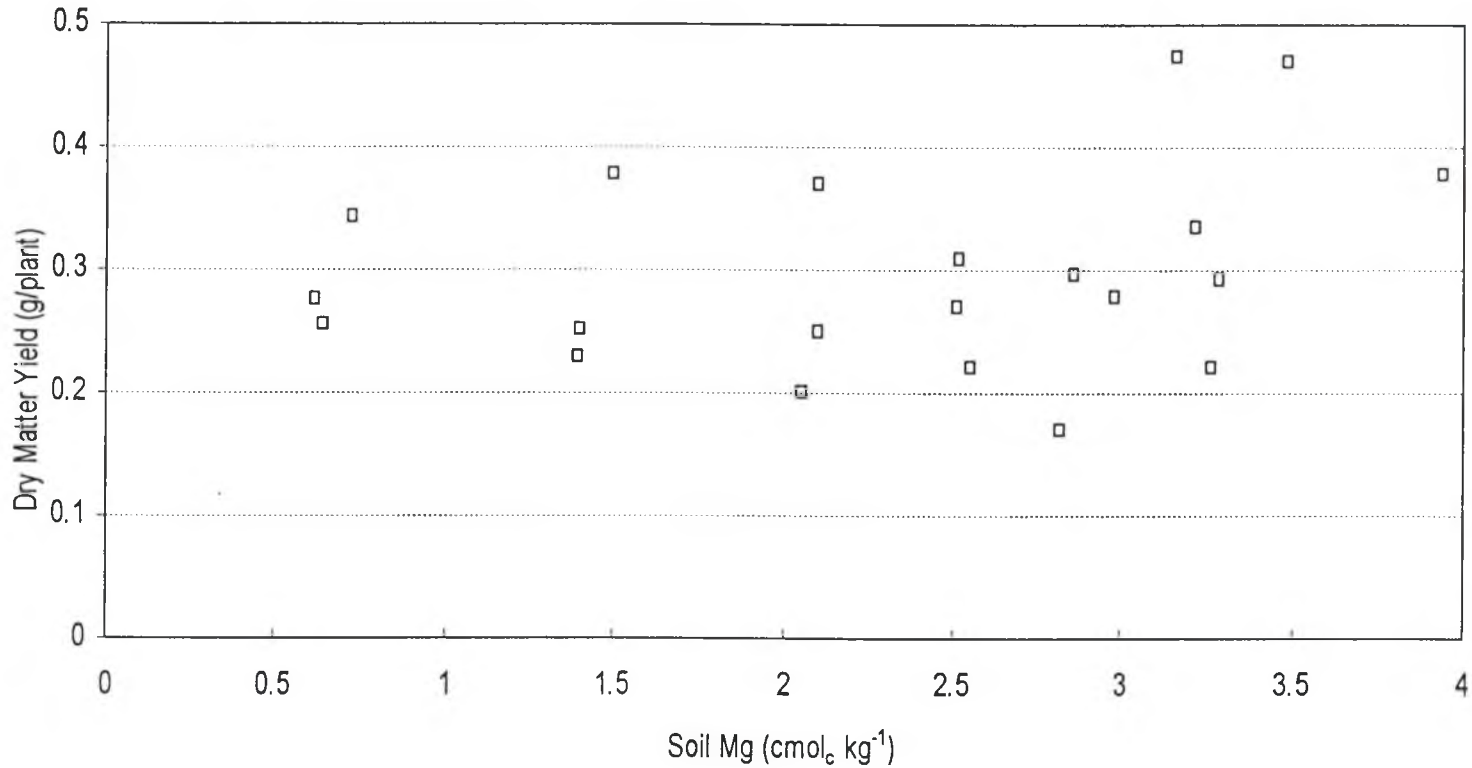

Figure 4-4. Yield Response of lettuce to soil Mg in the Manana soil series

Mg kg ha^{-1}	0	250	500	750	1000	1250	1500
Soil Mg cmol$_c$ kg^{-1}	0.67	1.43	2.08	2.53	3.16	3.35	3.17

Figure 4-5. Lettuce growth on different exchangeable soil Mg levels resulting from Mg treatments

Table 4-3. Analysis of Variance for Lettuce Yields with Mg Treatments

Source	DF	SS	MS	F	P
Mg treatment	6	0.02174	0.00362	0.46	0.8281
Replication	2	0.01574	0.00787	0.99	0.4003
Error	12	0.09551	0.00791		
Total	20	0.13299			

Table 4-4. Comparison of Mean Yield of Lettuce with Mg Treatments

Mg Treatments (Kg ha^{-1})	Mean (g $plant^{-1}$)
0	0.291
250	0.285
500	0.273
750	0.266
1000	0.371
1250	0.298
1500	0.301

Mg, Ca and the Ca/Mg ratio in the Mg experiment as independent variables indicated that these factors had no significant effects on dry matter yield (P=0.061, P=0.233 and P=0.785, respectively) and were not included in the regression model (Appendix E).

Yield Response to the Soil Ca/Mg Ratio

In the range of soil Ca/Mg ratios from 0.11 to 7.70 expressed on the basis of $cmol_c\ kg^{-1}$ (Figure 4-6), lettuce growth was decreased only by extremely low Ca/Mg ratios, i.e., around 0.11. No yield reduction was observed when Ca/Mg ratios were higher than 0.50.

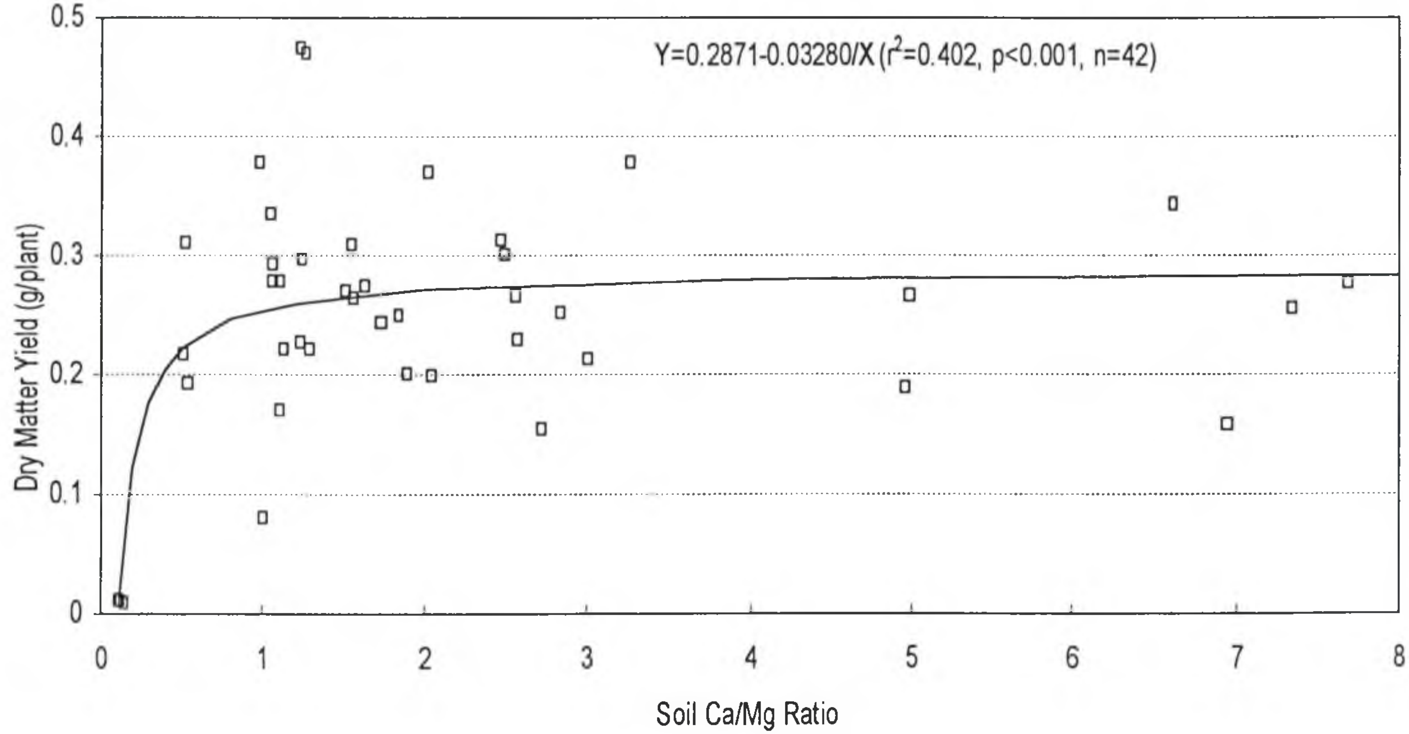

Figure 4-6. Yield Response of lettuce to soil Ca/Mg ratios in the Manana soil series

The low soil Ca level in association with the relatively high soil Mg level in the Ca experiment created a Ca deficiency that was the main cause of the extremely low yield of lettuce with the low Ca/Mg ratio. This agrees with some studies reported in the literature (MacLean & Finn, 1967; Van Lierop et al., 1979; Souza and Ritchey, 1988; Grant & Bailey, 1990), in which extremely low soil Ca/Mg ratios caused serious yield reductions. However, it should be pointed out that the yield reduction with the low Ca/Mg ratio in this study was accompanied by a low soil Ca level. Since it is difficult, if not impossible, to separate the low soil Ca effect from the low Ca/Mg ratio effect in this study in which the cation ratio can not be independent from cation levels, both soil Ca/Mg ratio and soil Ca or Mg level should be considered in interpreting the yield response to soil Ca/Mg ratios.

No yield reduction was observed in the range of soil Ca/Mg ratios from 0.50 to 7.70, which is within the optimal Ca/Mg ratio range considered by most studies reported in the literature (Moser, 1933; Hunter, 1949; Bear and Toth, 1948; Giddens and Toth, 1951; Halstead et al., 1958; Adams and Henderson, 1962; MacLean and Finn, 1967; Martin and Page, 1969; McLean and Carbonell, 1972; Spies, 1974; Simson et al., 1979; Van Lierop et al., 1979; Eckert amd McLean, 1981; McLean et al., 1983; Grant and Bailey, 1990; Franklin et al., 1991; Reid, 1996). This study provides more evidence for the conclusion that plants can grow normally with a broad range of Ca/Mg ratios. No information about high soil Ca/Mg ratios was obtained in this study because the highest Ca/Mg ratio was only 7.70 which is well within the optimal range. The main purpose of this study was to determine the critical soil Ca and Mg levels so evaluation of the Ca/Mg ratio is limited. More studies would have to be conducted to evaluate the effects of high

Ca/Mg ratios on crop growth and yield.

The relationship between lettuce yields and soil Ca/Mg ratios can be described by a ratio function:

$Y = 0.2871 - 0.0328/X$ ($r^2=0.402$, $P<0.001$, $n=42$) .... [2]

where Y is yield (dry matter) and X is soil Ca/Mg ratio.

Since the soil Ca/Mg ratio is co-varying with both soil Ca and Mg levels, caution must be used in interpreting crop response to the soil Ca/Mg ratio. Yield reduction at a low Ca/Mg ratio may be accompanied by low Ca or high Mg and the problem may be the low Ca or the high Mg or both and not the Ca/Mg ratio itself. Figure 4-7 shows the variation of soil Ca with the soil Ca/Mg ratio and their effects on yield. Furthermore, stepwise regression using soil Ca, soil Mg and the Ca/Mg ratio in the Ca experiment mentioned in page 30 shows that that both Ca and the Ca/Mg ratio had significant effects on dry matter yield and soil Ca appeared to have a greater effect than the soil Ca/Mg ratio.

Relationships between yield and plant Ca, Mg and the Ca/Mg ratio

The relationships between lettuce dry matter yield and plant Ca, Mg and the Ca/Mg ratio were similar to those for yield and soil Ca, Mg, and the Ca/Mg ratio. The relationship between yield and plant Ca level (Figure 4-8), which can be expressed by a quadratic function:

$Y=0.06075X-0.003019X2-0.0489$ ($r^2=0.564$, $P<0.001$, $n=21$) .... [3]

where Y is dry matter yield and X is plant Ca level. There was no significant relationship between yield and plant Mg level (Figure 4-9). The relationship between yield and plant Ca/Mg ratio can also be described by a ratio function (Figure 4-10):

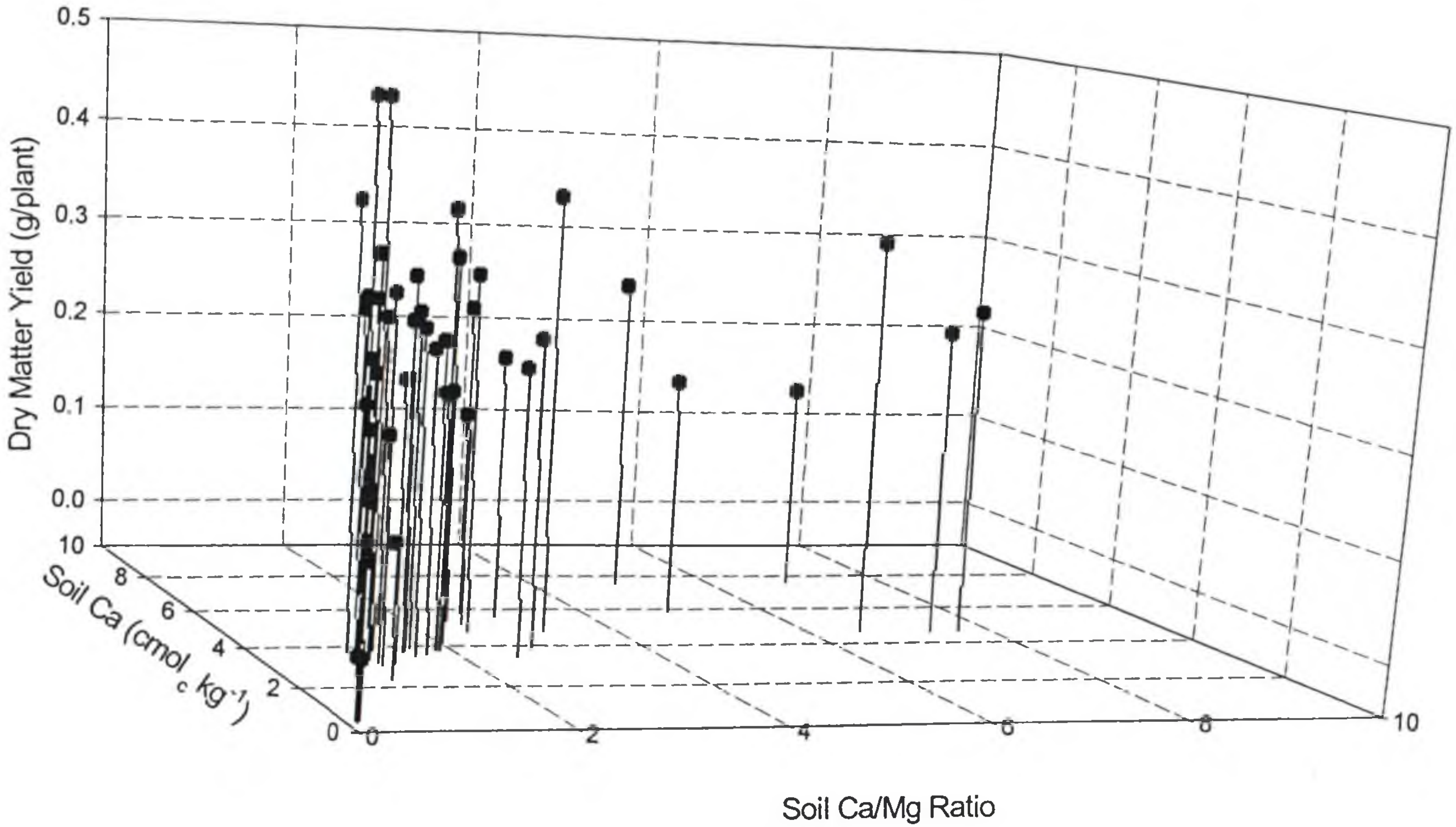

Figure 4-7. Lettuce Response to Soil Ca and Ca/Mg Ratio in the Ca and Mg Experiments

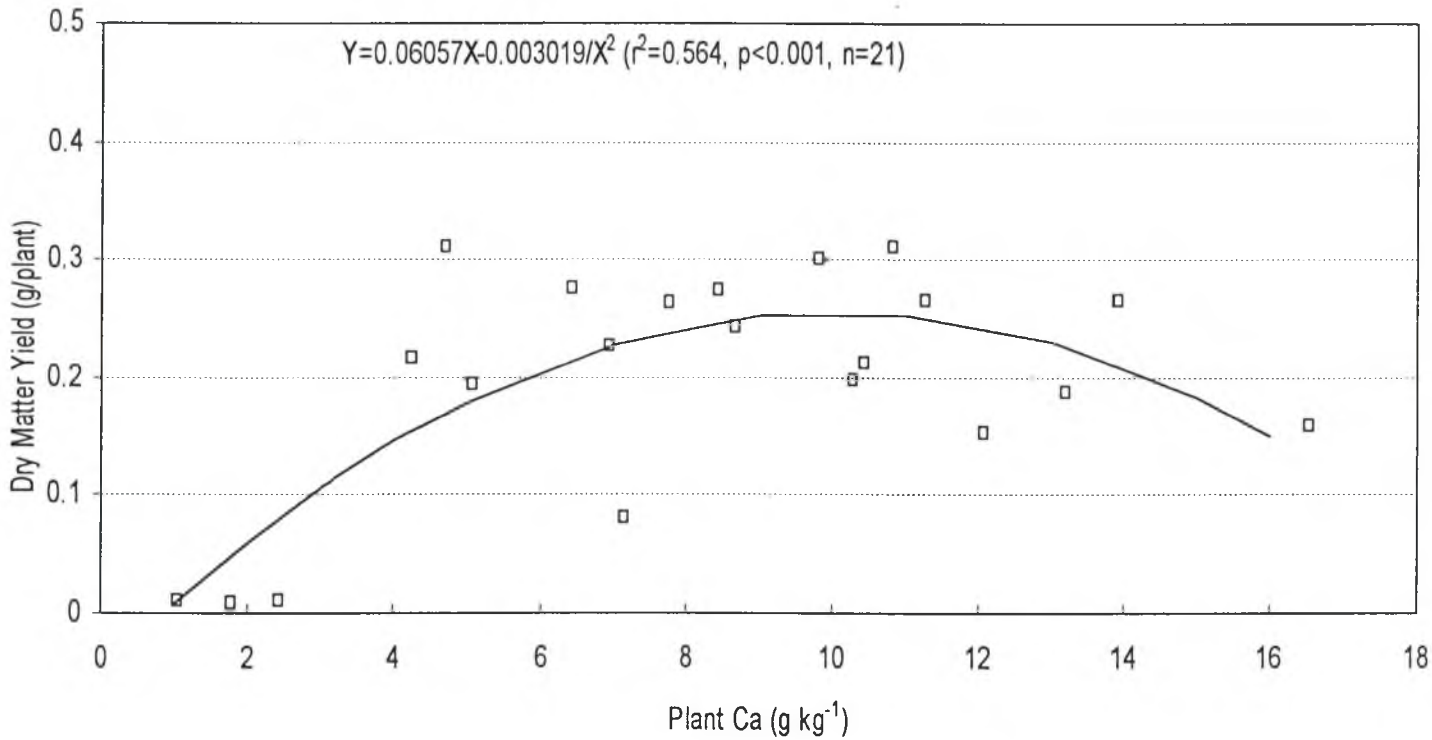

Figure 4-8. The relationship between dry matter yield and plant Ca

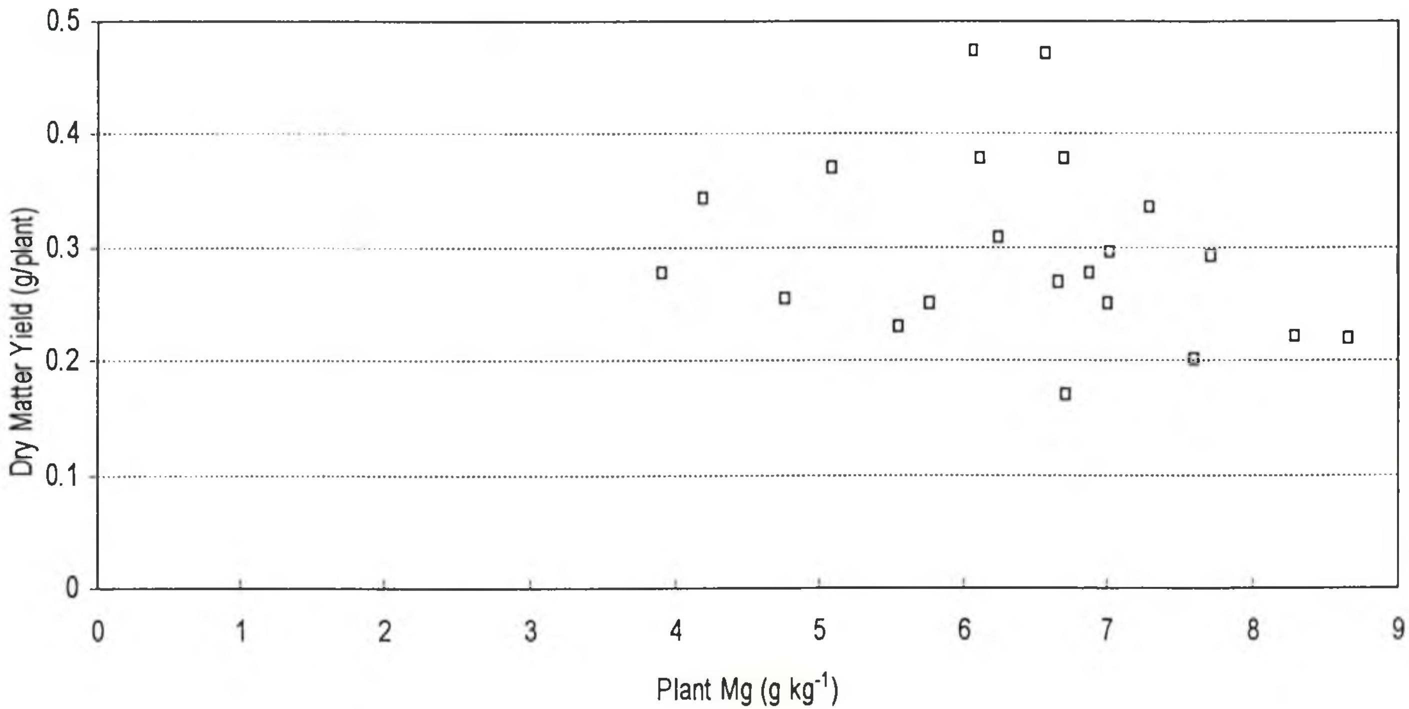

Figure 4-9. The relationship between dry matter yield and plant Mg

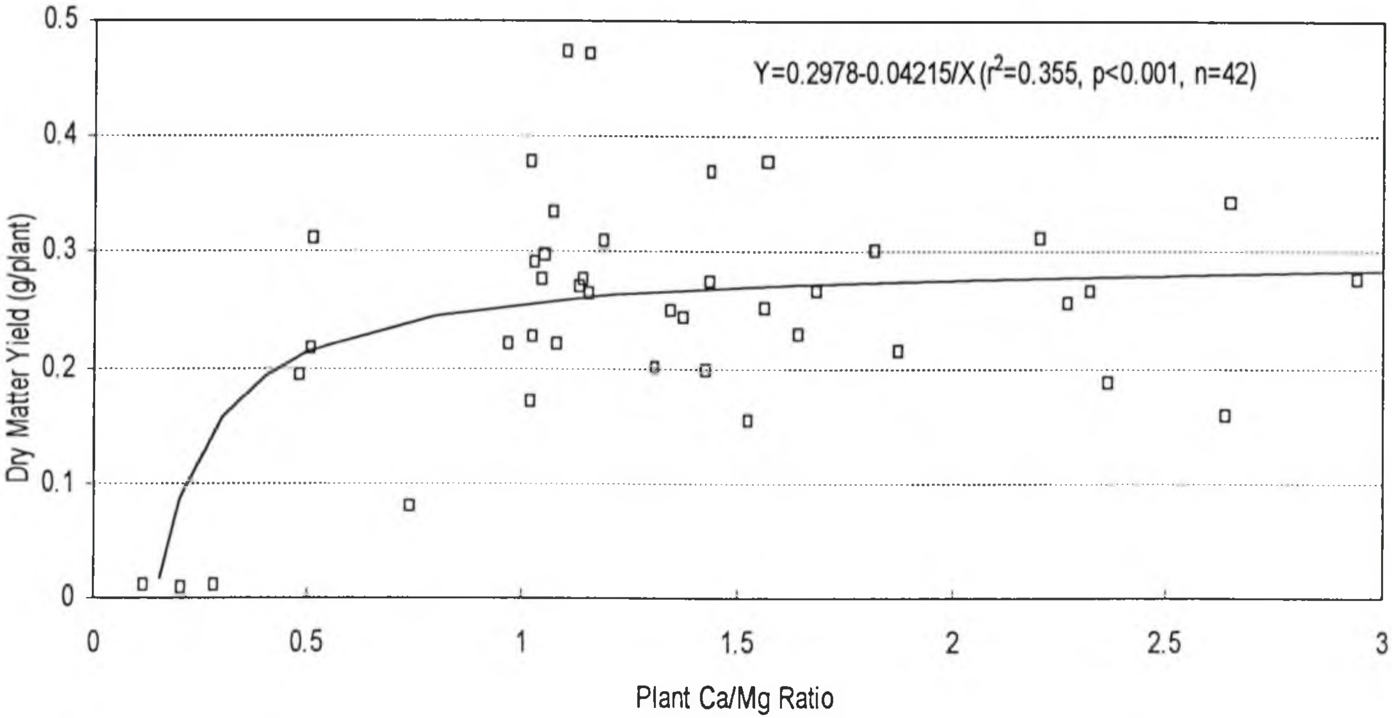

Figure 4-10. The relationship between dry matter yield and plant Ca/Mg ratios

$$Y=0.2978-0.04215/X \; (r^2=0.355, P<0.001, n=42) \quad \ldots\ldots\ldots\ldots \quad [4]$$

Where Y is dry matter yield and X is plant Ca/Mg ratio. The fact that the patterns of yield response with plant Ca, Mg and the Ca/Mg ratio were similar to the patterns of yield response with soil Ca, Mg and the Ca/Mg ratio suggests that there is a close relationship between soil and plant Ca, Mg and the Ca/Mg ratio.

Plants in the zero Ca treatment exhibited Ca deficiency symptoms and did not grow after the first 2 weeks from transplanting while plants continued to grow in the other treatments (Figure 4-11). Young leaves had marginal necrosis and the growing points died. Figure 4-12 shows Ca deficiency symptoms of lettuce grown in the zero Ca treatment. Soil Ca level was very low in this study, however, Mg based lime instead of Ca based lime was used to correct soil acidity and could not correct the low soil Ca problem which caused Ca deficiency of lettuce.

Lettuce did not show Mg deficiency symptoms in the zero Mg treatment and grew well on all Mg treatments (Figure 4-13).

Critical levels of Soil Ca & Mg Nutrients for Lettuce

Soil Ca

The critical soil Ca level found in the literature ranges from 1 to 3 $cmol_c\ kg^{-1}$ depending on the soil, crop and other conditions (Kamprath, 1984; Melsted, 1953; McLean, 1982; Andrew and Norris, 1961 and Haby et al., 1990). A critical soil Ca level for lettuce on the acid Manana soil series used in this study determined by the Cate-Nelson method (Cate and Nelson, 1965) is 1.9 $cmol_c\ kg^{-1}$ (Figure 4-14). Although the yield

Ca $kg\ ha^{-1}$	0	1000
Soil Ca $cmol_c\ kg^{-1}$	0.57	1.92

Figure 4-11. Lettuce growth on the 3 replications of the zero Ca treatment and the 1000 kg ha^{-1}Ca treatment on the Manana soil series

Figure 4-12. Ca deficiency symptoms of lettuce grown on the zero Ca treatment

Mg $kg\ ha^{-1}$	0	250
Soil Mg $cmol_c\ kg^{-1}$	0.67	1.43

Figure 4-13. Lettuce growth on the 3 replications of the zero Mg treatment and the 250 kg ha^{-1} treatment on the Manana soil series

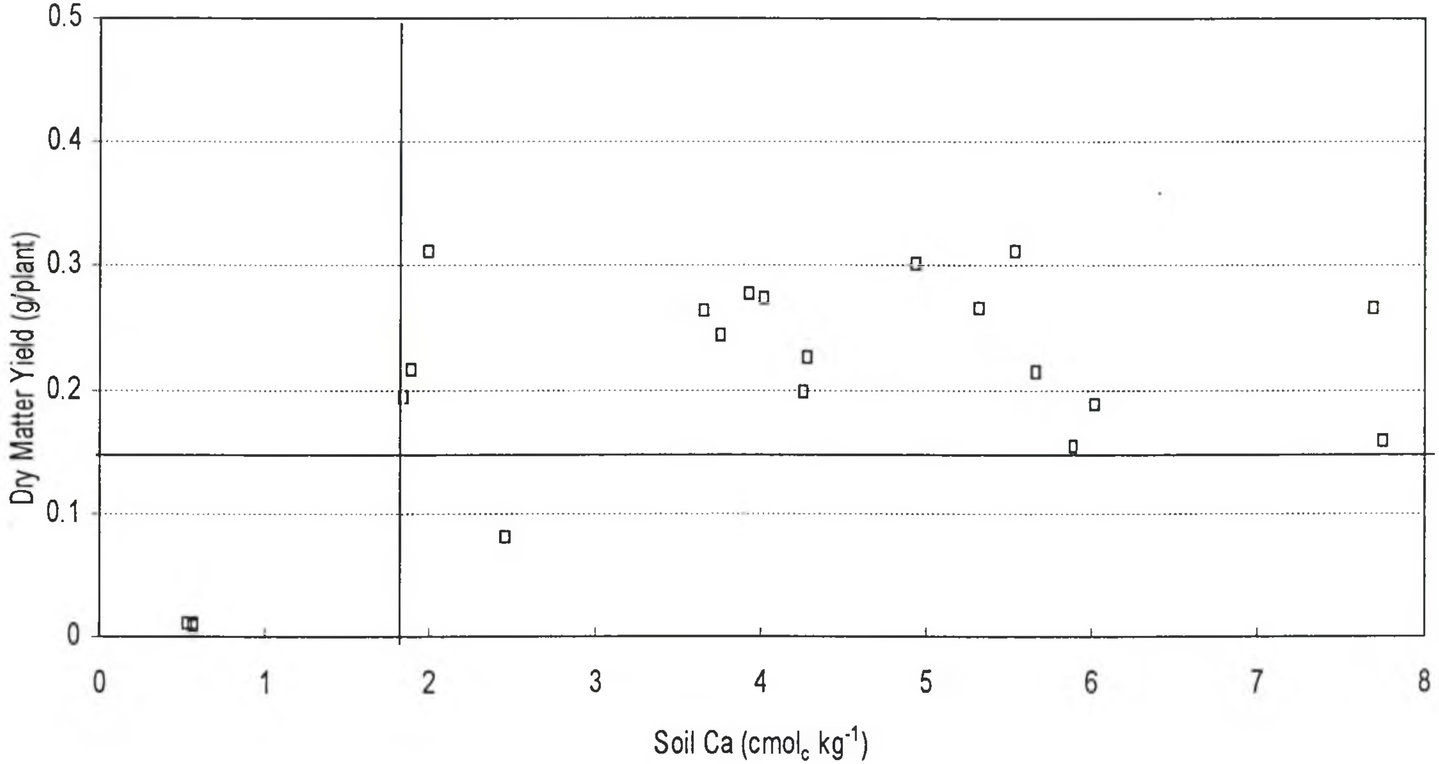

Figure 4-14. Determination of the critical level of soil Ca for lettuce in the Manana soil series by the Cate-Nelson method

response data in this study indicated that the critical Ca level could have been set between 0.6 and 1.9 $cmol_c\ kg^{-1}$, the critical level of 1.9 $cmol_c\ kg^{-1}$ was selected to minimize the possibility of applying inadequate amounts of Ca to lettuce and reduce the chance of Ca deficiency. This critical level is more reasonable and lower than the 5 $cmol_c\ kg^{-1}$ that is currently recommended in Hawaii. It appears that more experiments are needed to establish critical soil Ca levels on different soils and crops in Hawaii.

Soil Mg

The critical soil Mg level found in the literature ranges from 0.06 to 0.60 $cmol_c\ kg^{-1}$ depending on the soil, crop and other conditions (Adams, 1984; McLean, 1982; McLean and Carbonell, 1972; Fox and Piekielek, 1984 and Haby et al., 1990). A critical soil Mg level for lettuce on the acid Ultisol in Hawaii could not be established in this study because there was no yield response to Mg applications, but the data do suggest that soil Mg levels of 0.67 $cmol_c\ kg^{-1}$ or above are adequate for lettuce. Further studies on soil with lower soil Mg are needed to more closely define the critical soil Mg level in Hawaii. However, it appears that the sufficiency range for soil Mg used in Hawaii (2.5 $cmol_c\ kg^{-1}$ to 3.3 $cmol_c\ kg^{-1}$) is too high based on the findings of this study.

Soil Ca/Mg ratio

The lower critical level for soil Ca/Mg ratio was identified as 0.5 on the basis of $cmol_c\ kg^{-1}$ in the literature (MacLean and Finn, 1967; Van Lierop et al., 1979; Souza and Ritchey,1988 and Grant and Bailey, 1990). The lower critical level for the soil Ca/Mg ratio for lettuce on the acid Manana soil series in this study was determined by the Cate-Nelson method (Cate and Nelson, 1965) to be 0.5 (Figure 4-15). Below this critical level,

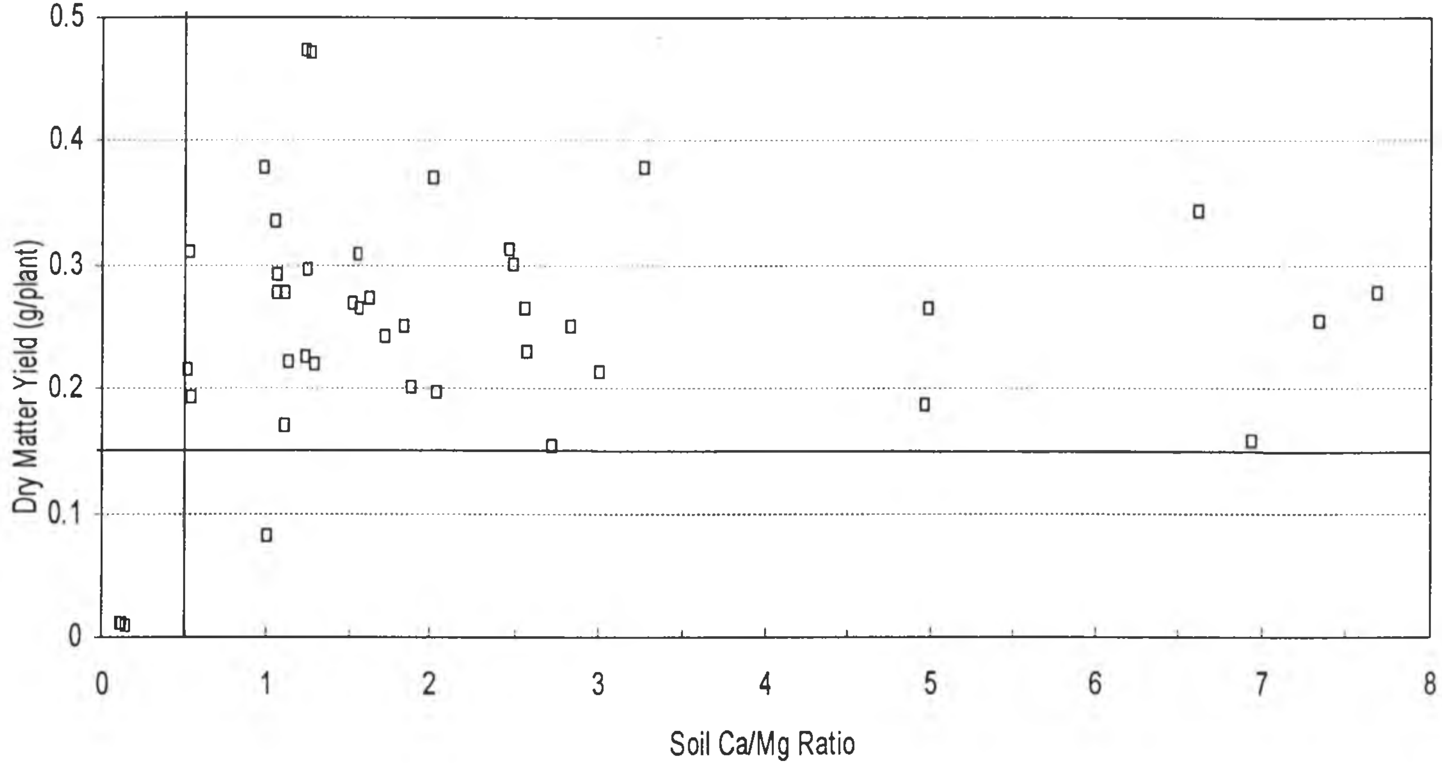

Figure 4-15. Determination of the critical level of soil Ca/Mg ratios for lettuce in the Manana soil series by the Cate-Nelson method

serious yield reductions are expected to occur due to Ca deficiency and other nutrient problems caused by imbalance between Ca and Mg. This extremely low Ca/Mg ratio situation may occur in the field when applying Mg based lime to acid soils with low Ca levels and/or irrigating Ca poor soil with irrigation water high in Mg. It should be pointed out that since soil Ca/Mg ratio is co-varying with both soil Ca and Mg levels, caution should be taken in interpreting the critical lower soil Ca/Mg ratio. Low Ca or high Mg should be also considered in recommending liming and fertilization.

Critical levels for Plant Ca & Mg Nutrients for Lettuce

Plant Ca concentration

The critical plant Ca concentration for lettuce is reported to range from 4.3~13 g kg^{-1} depending on the plant part sampled, crop age and other conditions according to Jones et al. (1991) and Reuter and Robinson (1986). A critical plant Ca concentration for lettuce at maturity on the acid Manana soil series in Hawaii, used in this study, was determined to be 4 g kg^{-1} (Figure 4-16) by the Cate-Nelson method (Cate and Nelson, 1965). It is interesting to note that plant Ca reflects the level of available soil Ca. Both soil and plant critical levels can be determined when a crop responds to increasing levels of a nutrient. The critical plant Ca concentration is an indicator of plant Ca status as well as available soil Ca. Detailed discussion will be presented on the section of the effect of soil Ca on plant nutrient uptake.

Plant Mg concentration

The critical plant Mg concentration for lettuce is reported to range from 3~5 g kg^{-1} depending on the plant part sampled, crop age and other conditions (Jones et al., 1991;

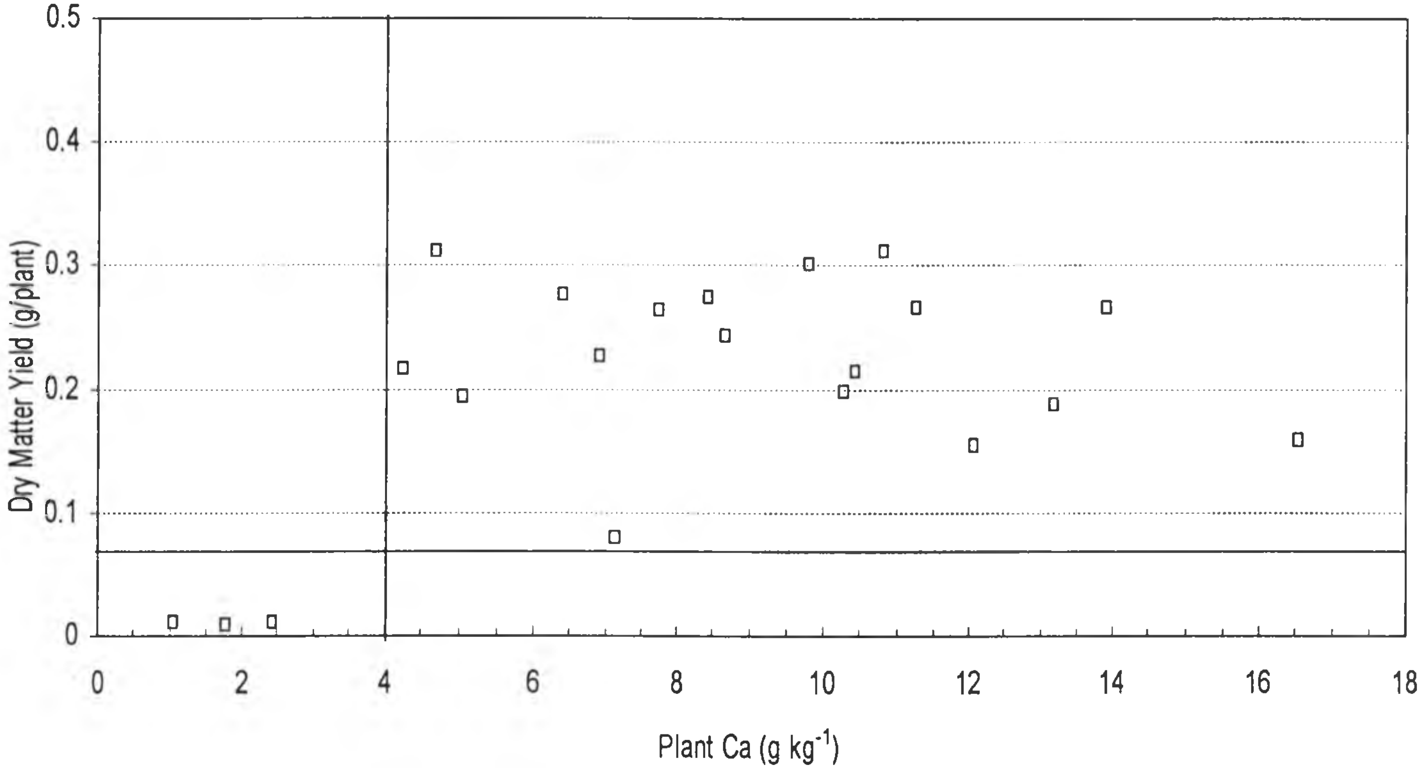

Figure 4-16. Determination of the critical level of plant Ca for lettuce by the Cate-Nelson method

Reuter and Robinson, 1986). A critical plant Mg concentration for lettuce at maturity on the acid Manana soil series in Hawaii could not be determined in this study because there was no crop response to increasing levels of soil Mg, however, data from this study suggest that plant Mg level of 4 g kg^{-1} and above are adequate for normal growth of lettuce. It is also interesting to note that plant Mg nutrient concentration reflects the levels of available soil Mg. Both soil and plant critical levels, however, can be determined more accurately when a crop responds to increasing levels of a nutrient. Detailed discussion will be presented in the section on the effect of soil Mg on plant nutrient uptake.

Plant Ca/Mg ratio

No critical level for plant Ca/Mg concentration ratio of lettuce was found in the literature. In this study, a critical plant Ca/Mg concentration ratio for lettuce at maturity on the acid Manana soil series in Hawaii was determined to be 0.5 (Figure 4-17) by the Cate-Nelson method (Cate and Nelson, 1965). Similar to the soil Ca/Mg ratio, the plant Ca/Mg nutrient ratio can also be a good indicator of plant nutrient status. Detailed discussion of the relationship between soil Ca/Mg ratio and plant Ca/Mg ratio will be presented in the section of the effect of soil Ca/Mg ratio on plant Ca/Mg ratio.

The Effect of Soil Ca on Other Soil Cations

Exchangeable soil cations interact with each other and application of a large amount of liming material can cause cation imbalance. The Ca and Mg experiments in this study provided an opportunity to investigate the change in soil nutrient status as varying amounts of Ca and Mg were applied to an acid tropical soil. Moreover, since soil

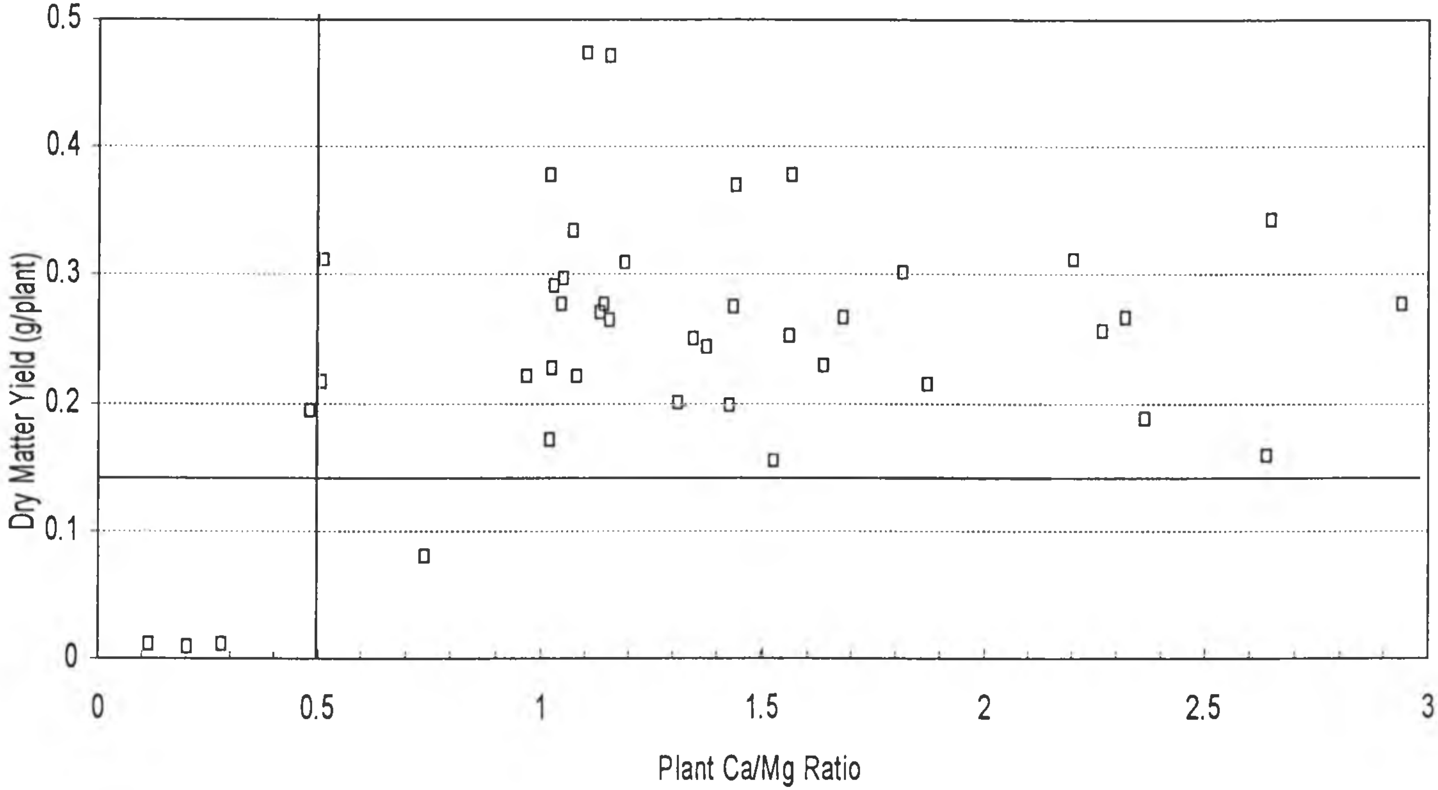

Figure 4-17. Determination of the critical level of plant Ca/Mg ratios for lettuce by the Cate-Nelson method

solution leaching plays an important role in the dynamics of soil nutrients in tropical areas where rainfall is high and concentrated, the soil solution leaching conducted in this study to minimize salt effects simulated the soil solution leaching process that occurs in the field. This provided an opportunity to study the effects of leaching on the dynamics of the movement of soil nutrients following the application of large amounts of liming material. In the Ca experiment, soil Mg decreased as soil Ca increased (Figure 4-18). A high negative correlation was found between them ($r=-0.871$, $P<0.001$, $n=21$). Similarly, soil K decreased with an increase of soil Ca (Figure 4-19). The negative correlation between them was also high ($r=-0.835$, $P<0.001$, $n=21$). Moreover, soil Na followed the same pattern as soil Mg and K and its decrease was very highly, negatively correlated ($r=-0.924$, $P<0.001$, $n=21$) with increasing soil Ca (Figure 4-20). When high amounts of one cation are applied to soil, the other cations will decrease as the soil solution is leached from the profile. Therefore, application of Ca based lime increased soil Ca and reduced the availability of other cations in the soil due to leaching losses.

The Effect of Soil Mg on Other Soil Cations

The Mg experiment provided information about the effect of high amounts of Mg on leaching losses of other cations. Soil Ca decreased as soil Mg increased (Figure 4-21) and the negative correlation between them ($r=-0.633$, $P<0.01$, $n=21$) was significant. Similarly, soil K decreased with an increase in soil Mg (Figure 4-22). The negative correlation between them was also significant ($r=-0.637$, $P<0.01$, $n=21$). Likewise, soil Na followed a similar pattern as soil Ca and K and its decrease was highly correlated ($r=-0.912$, $P<0.001$, $n=21$) with the increase in soil Mg (Figure 4-23). Because the amount

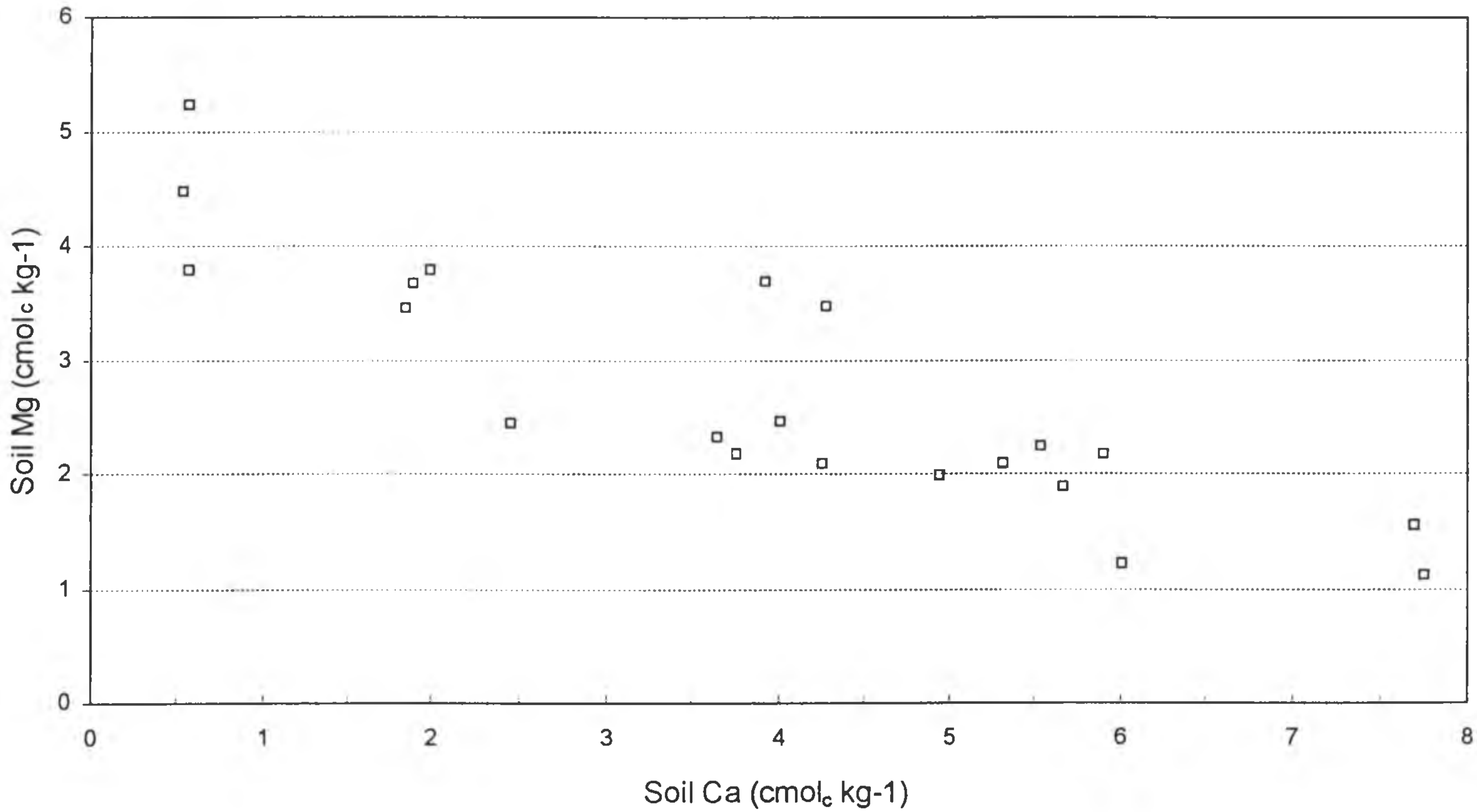

Figure 4-18. The effect of soil Ca on soil Mg in the Manana soil series

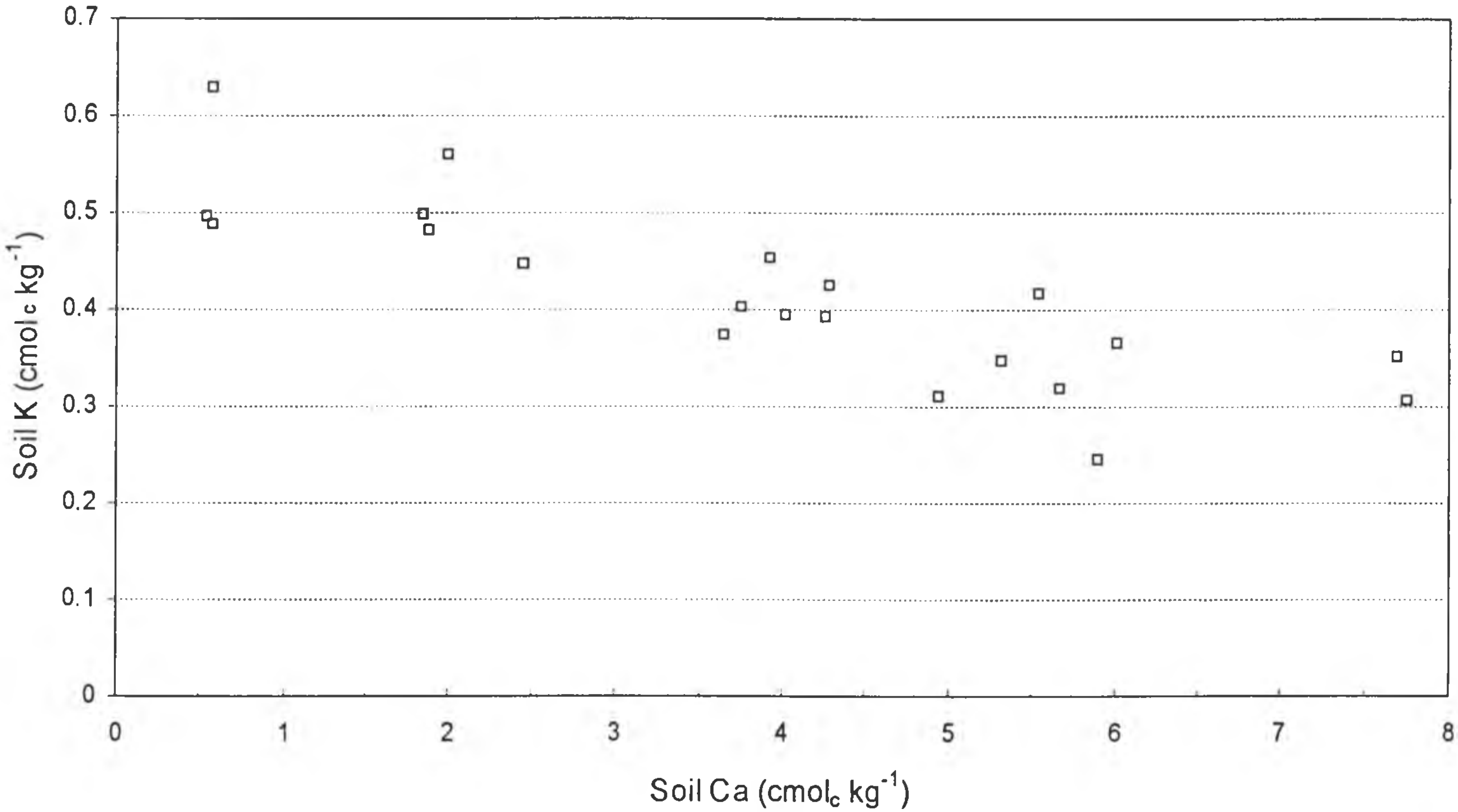

Figure 4-19. The effect of soil Ca on soil K in the Manana soil series

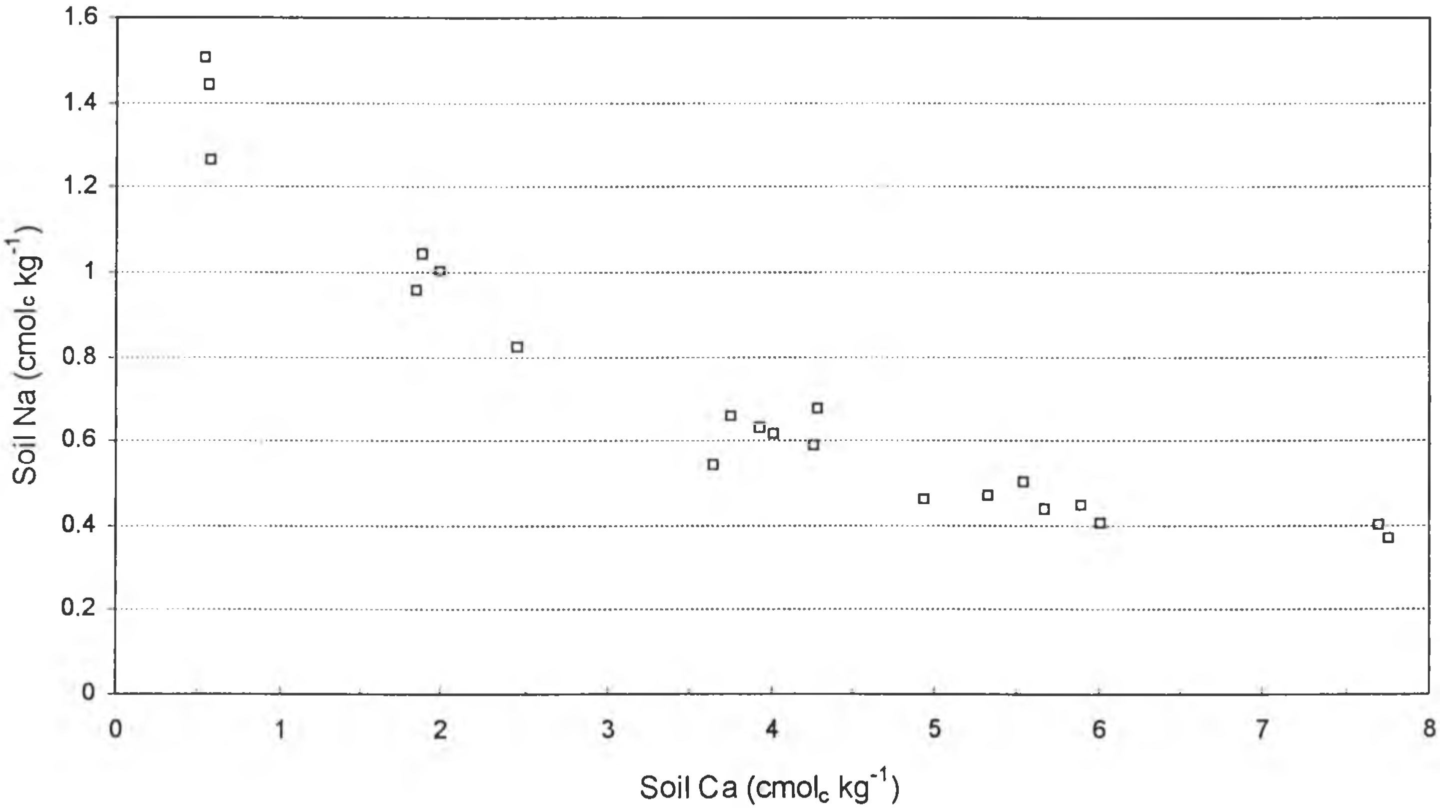

Figure 4-20. The effect of soil Ca on soil Na in the Manana soil series

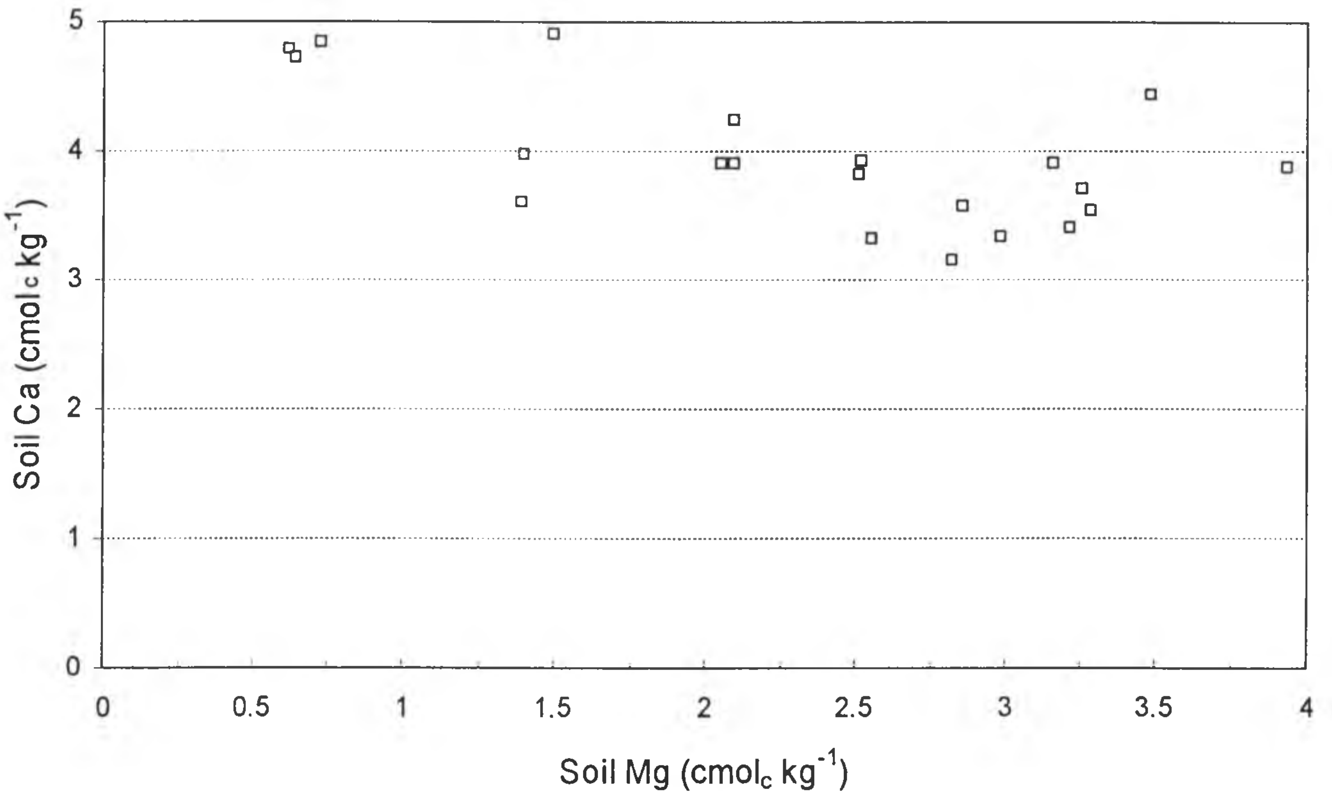

Figure 4-21. The effect of soil Mg on soil Ca in the Manana soil series

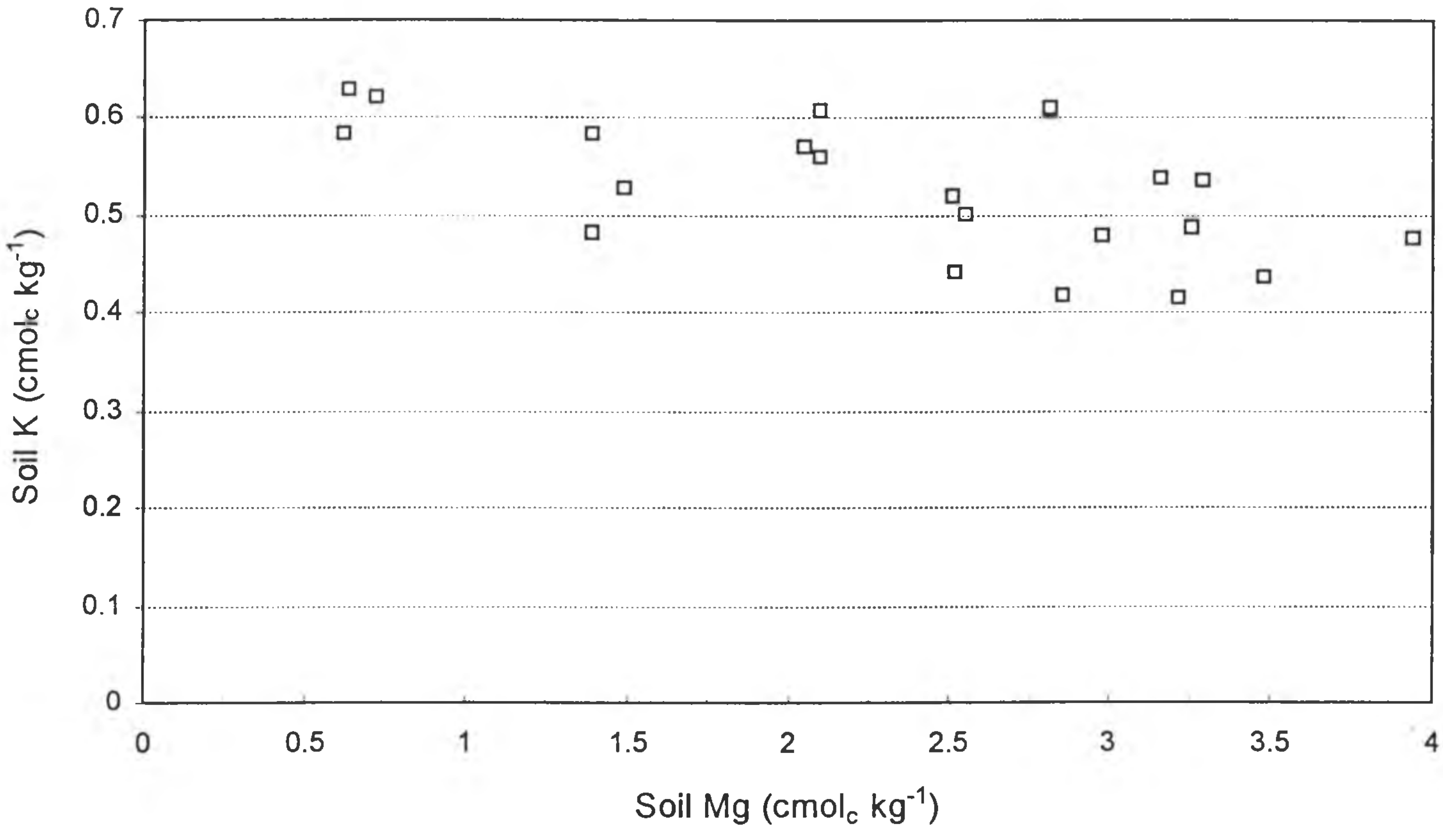

Figure 4-22. The effect of soil Mg on soil K in the Manana soil series

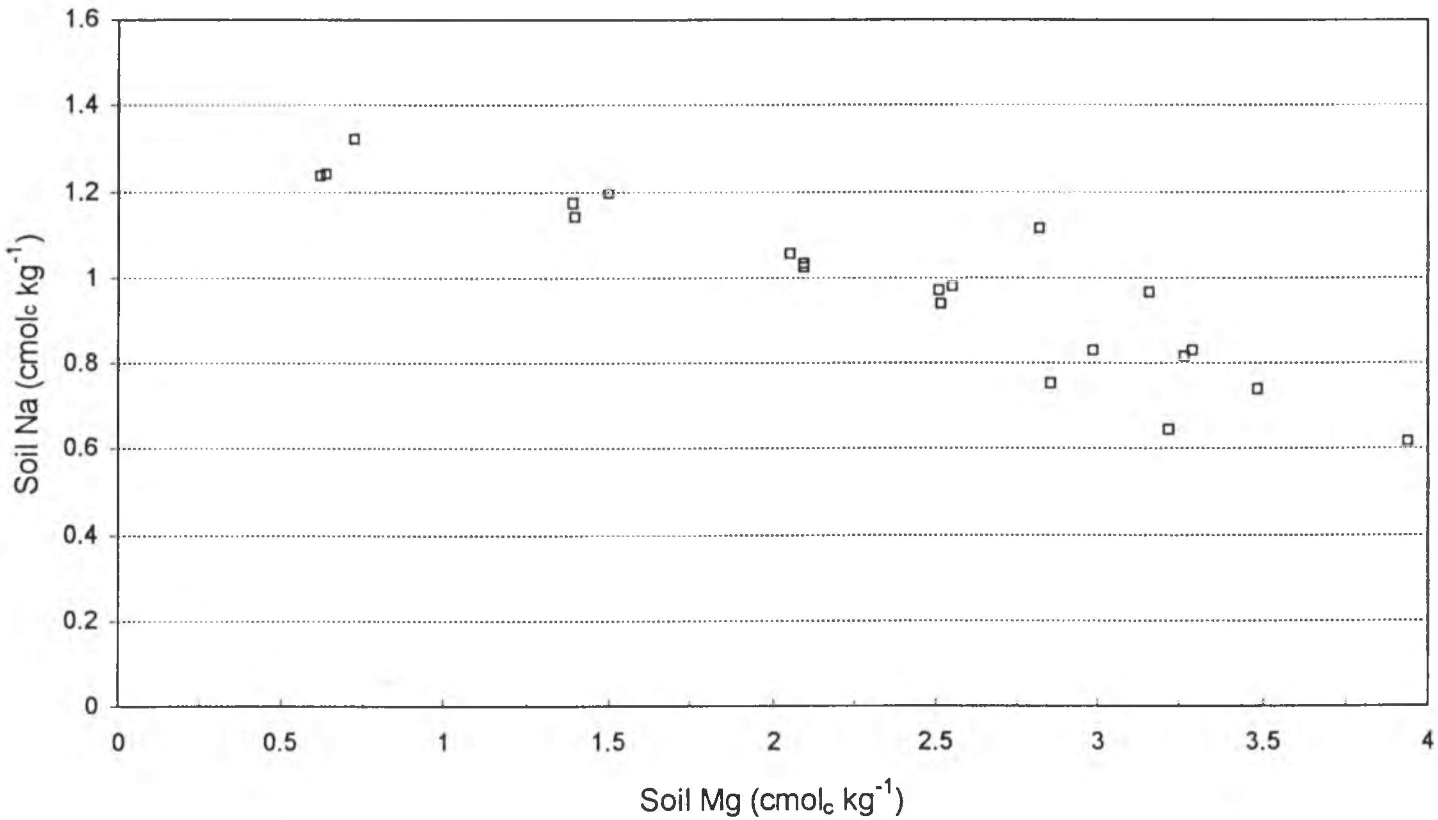

Figure 4-23. The effect of soil Mg on soil Na in the Manana soil series

of Mg applied to soil was much smaller than those of Ca, the relationships between Mg and the other cations are weaker than that of Ca. However, since soil Ca level was low in the original soil, application of a moderate amount of Mg based lime in the Ca experiment resulted in Ca deficiency in plants grown on the zero Ca treatment. Therefore, nutrient balance must be considered to avoid creating deficiencies of other cations when lime is applied to acid tropical soils.

The Effect of Soil Ca on Plant Nutrient Uptake

In the Ca experiment, plant uptake of Ca was very highly, positively related to soil Ca levels (Figure 4-24). The relationship was linear with $r=0.970$ ($P<0.001$, $n=21$). Plant Mg uptake, on the other hand, decreased as soil Ca increased (Figure 4-25). The effect of soil Ca on other plant cations is indirect because leaching the soil following application of varying amounts of Ca removed varying amounts of other cations that affected plant uptake of these cations. The negative correlation of soil Ca with plant Mg was significant ($r=-0.747$, $P<0.001$, $n=21$) and reflected the relationship between soil Ca and soil Mg (Figure 4-18). Plant uptake of Na, like plant Mg, was also reduced as a result of the decreased soil Na levels (Figure 4-26). The negative correlation of soil Ca with plant Na was also significant ($r=-0.869$, $P<0.001$, $n=21$). However, although soil K levels were reduced by the increase in soil Ca, plant K uptake did not appear to follow the same pattern (Figure 4-27). The low K uptake at the low soil Ca level may be explained by the important role of Ca in stabilizing membranes. Clark (1984) reviewed experiments dealing with the effects of Ca on selective ion uptake and leaking of cells. Low Ca levels had adverse effects on the selective uptake of monovalent cations such as K. Closely

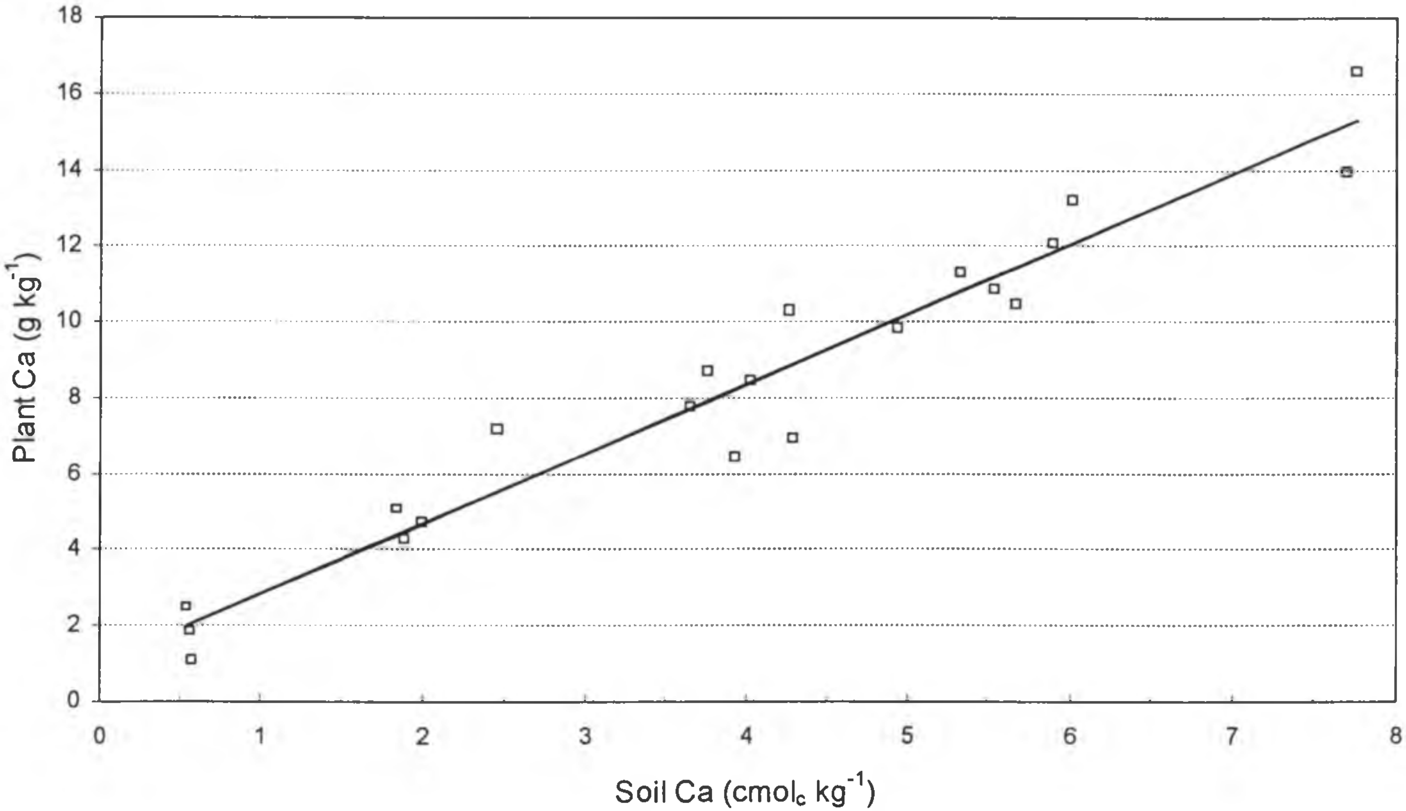

Figure 4-24. The relationship between soil Ca and plant Ca in lettuce

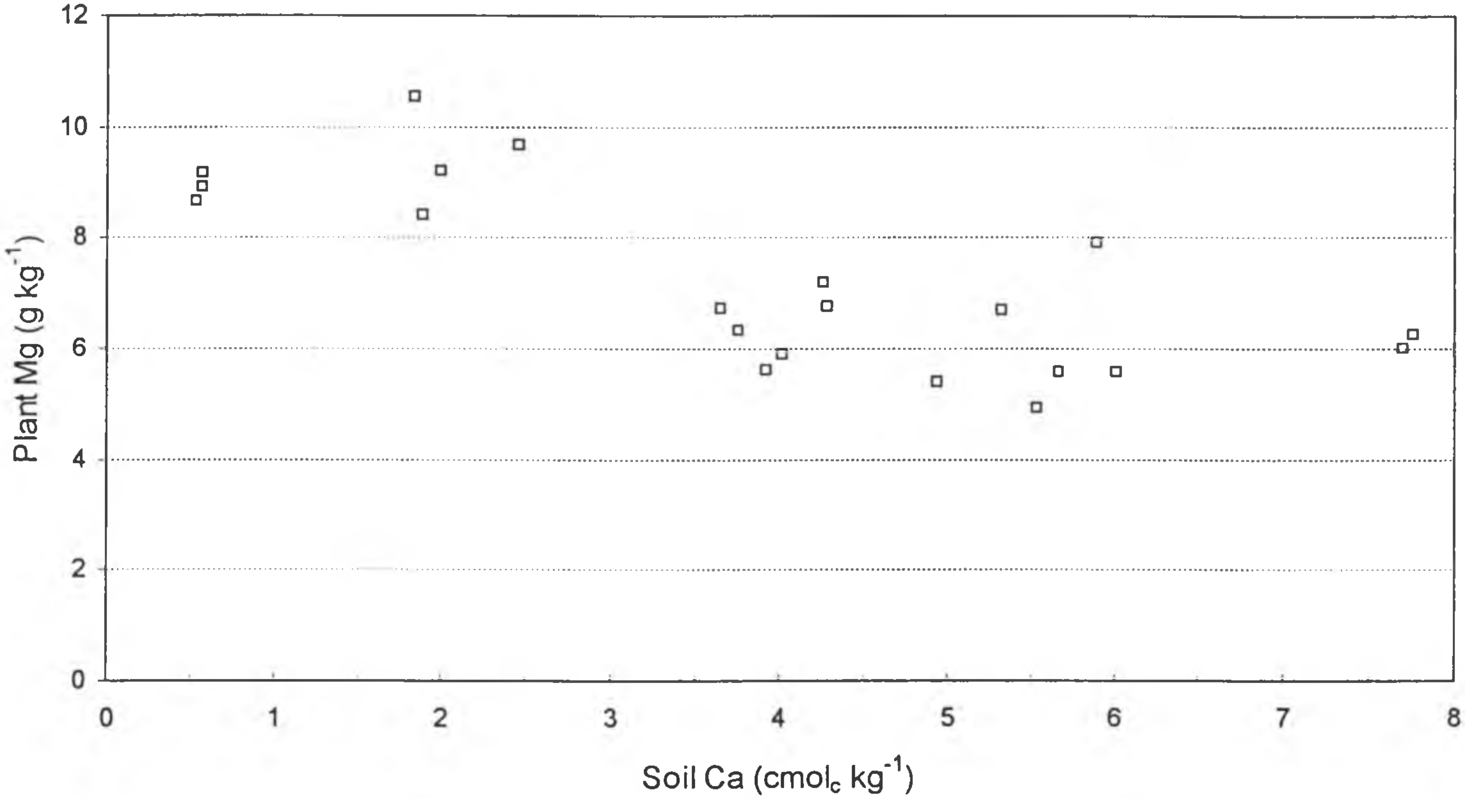

Figure 4-25. The relationship between soil Ca and plant Mg in lettuce

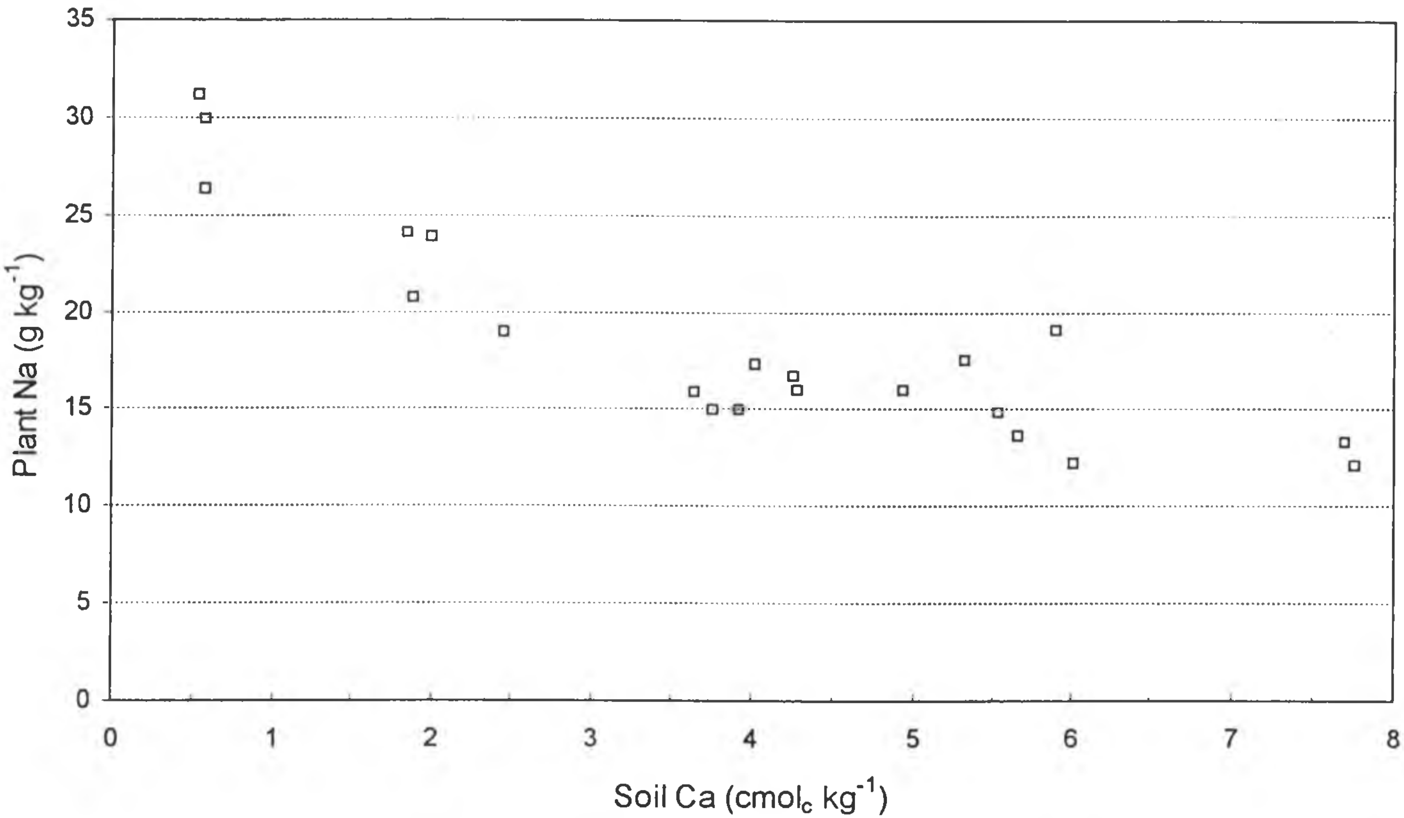

Figure 4-26. The relationship between soil Ca and plant Na in lettuce

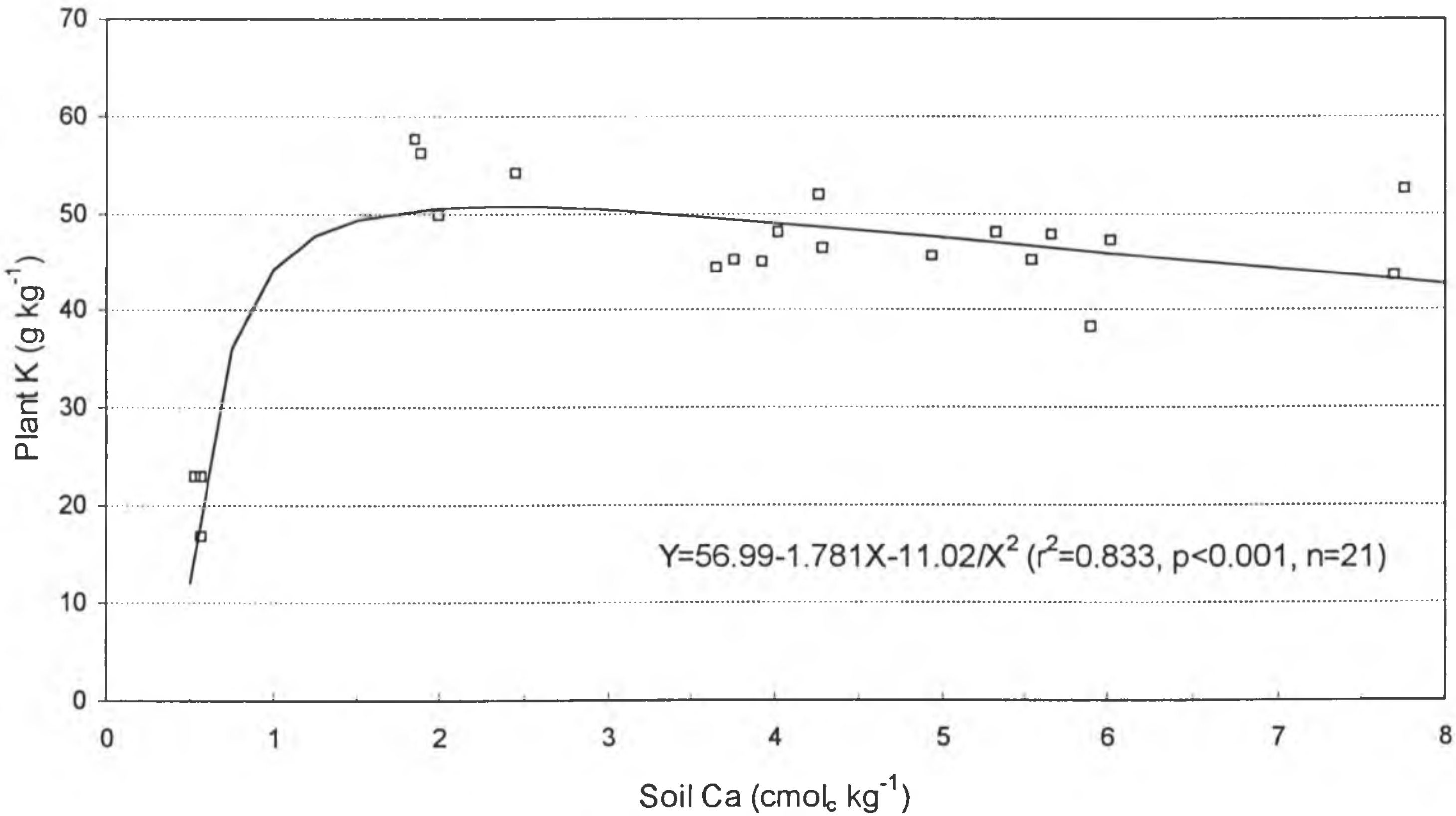

Figure 4-27. The relationship between soil Ca and plant K in lettuce

associated with selective ion uptake by membranes is the leakiness, or increased premeability, of membranes at low Ca levels, which can allow K to leak out. When soil Ca is adequate, K uptake is not controlled by Ca but by soil K levels. Therefore, the relationship between soil Ca level and plant K uptake can be described by a quadratic function:

$$Y= 56.99-1.781X-11.02/X^2 \ (r^2=0.833, P<0.001, n=21) \quad \ldots\ldots\ldots\ldots\ldots \quad [5]$$

where Y is plant K level and X is soil Ca level. It is very interesting to observe this plant K uptake phenomenon that provided evidence for the importance of Ca in plant nutrition. Moreover, there was no significant correlation between soil Ca level and plant P uptake (Figure 4-28) with $r=-0.3809$ ($P>0.05$, $n=21$). Since soil P is an anion and its behavior is different from that of cations, soil Ca appeared to have no effect on soil P or plant P. These results indicate that leaching a soil after Ca has been applied resulted in increased soil Ca and plant uptake of Ca but reduced plant uptake of Mg and Na. However, plant uptake of K and P appeared to be unaffected.

The Effect of Soil Mg on Plant Nutrient Uptake

Plant uptake of Mg was highly, positively related to soil Mg levels in the Mg experiment (Figure 4-29). The relationship between soil Mg and plant Mg was linear with $r=0.7231$ ($P<0.001$, $n=21$). Plant Ca, on the other hand, decreased significantly ($r=-0.8535$, $P<0.001$, $n=21$) as soil Mg level increased (Figure 4-30). This is also an indirect effect because leaching soil containing increasing amounts of soil Mg resulted in varying amounts of other cations available for plant uptake. Plant uptake of Na, like plant Ca uptake, was also reduced as a result of the decrease of soil Na levels (Figure 4-31) with

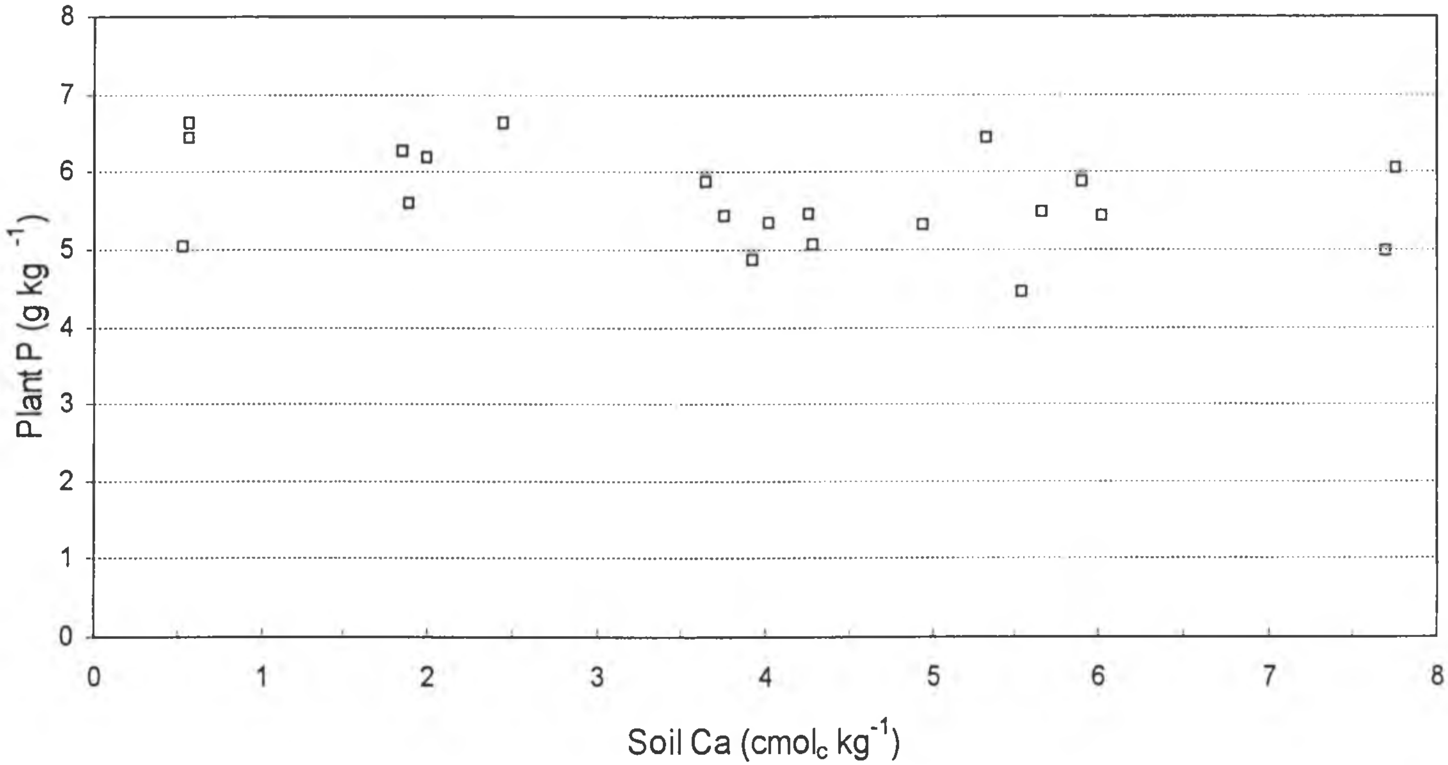

Figure 4-28. The relationship between soil Ca and plant P in lettuce

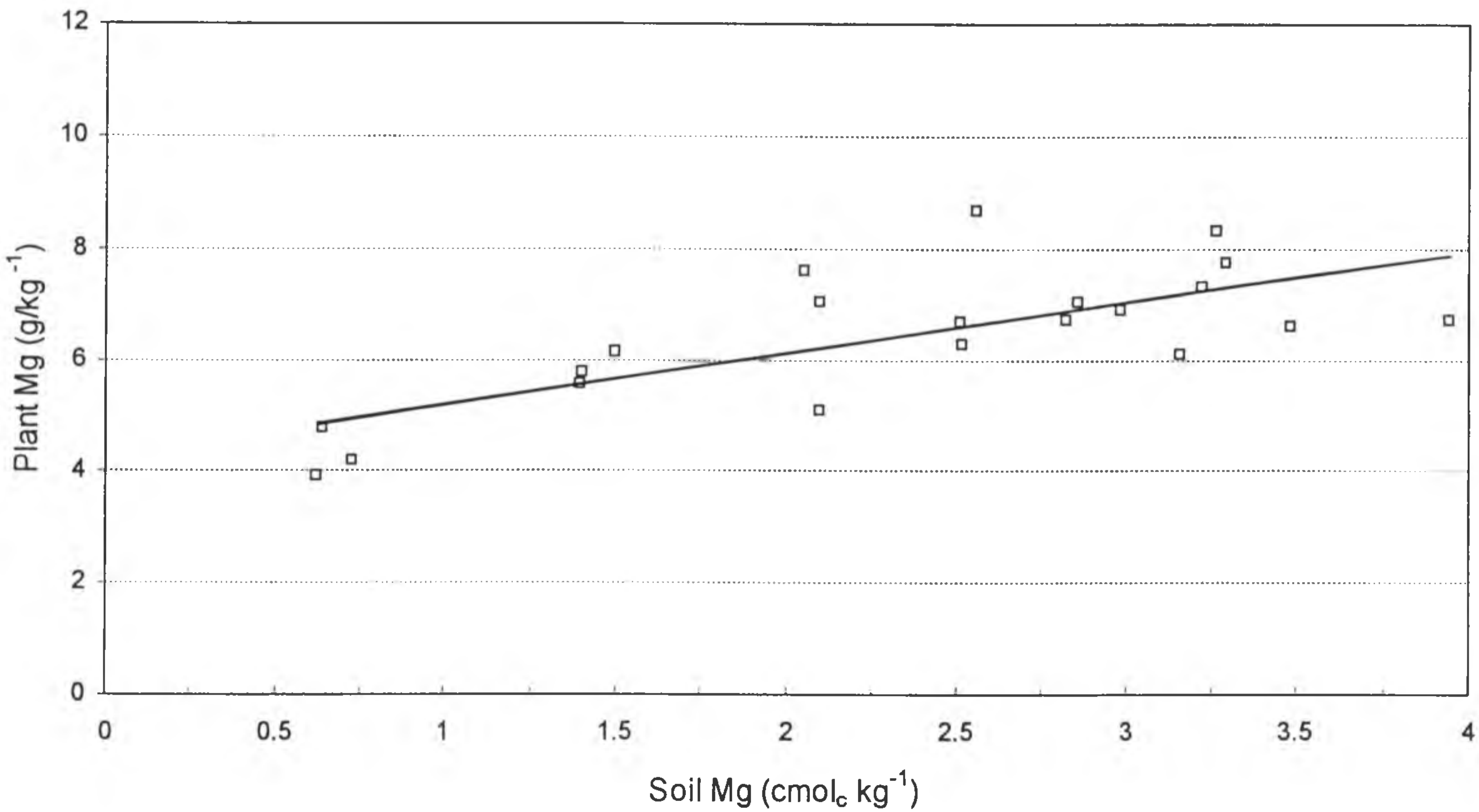

Figure 4-29. The relationship between soil Mg and plant Mg in lettuce

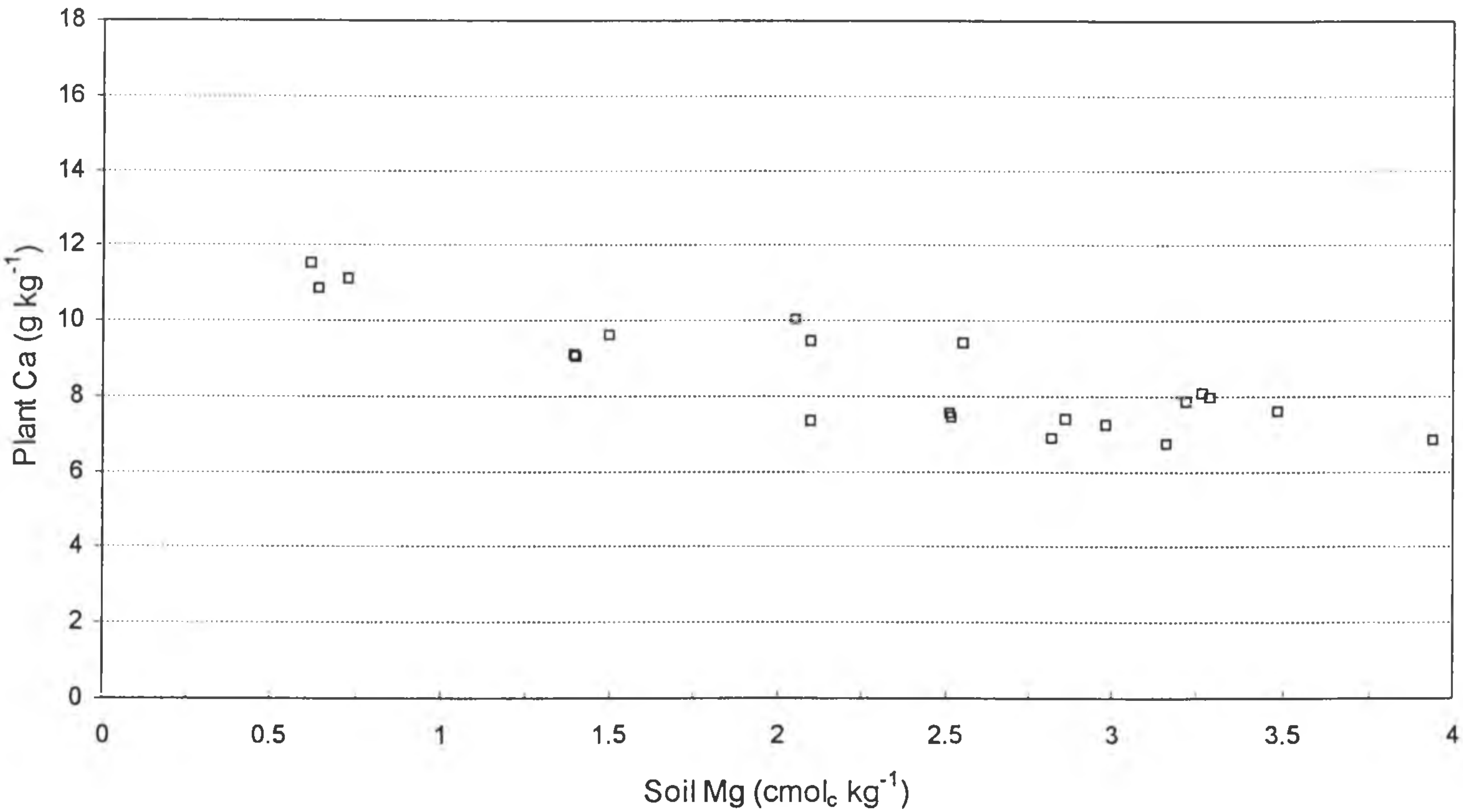

Figure 4-30. The relationship between soil Mg and plant Ca in lettuce

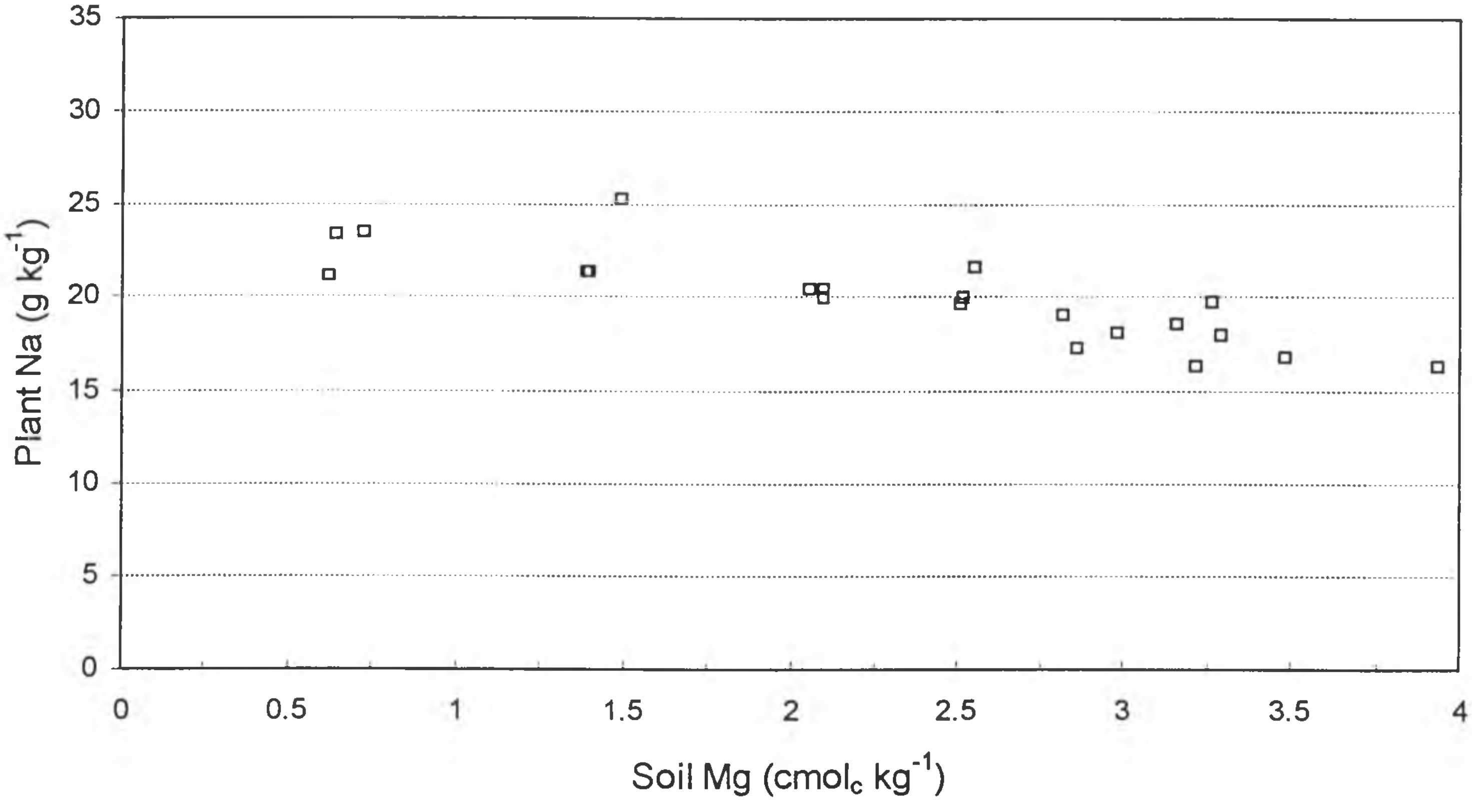

Figure 4-31 The relationship between soil Mg and plant Na in lettuce

increasing soil Mg . A highly negative correlation coefficient was found in this relationship ($r=-0.8426$, $P<0.001$, $n=21$). Although soil K levels were reduced with increased soil Mg, plant uptake of K did not appear to be affected (Figure 4-32). There was no significant negative relationship between soil Mg levels and plant K uptake ($r=0.0006$, $P>0.05$, $n=21$). Moreover, there was no correlation between soil Mg levels and plant P uptake (Figure 4-33) with $r=0.1852$ ($P>0.05$, $n=21$). Soil P as an anion behaves quite differently from cations, therefore, soil P or plant P are not expected to be affected by soil Mg levels. The results of the Mg experiment indicate that leaching a soil after Mg has been applied resulted in increased soil Mg and plant uptake of Mg but reduced plant uptake of Ca and Na. However, plant uptake of K and P appeared to be unaffected.

The Effect of the Soil Ca/Mg ratio on the Plant Ca/Mg ratio

Plant Ca/Mg ratios in lettuce were significantly affected by soil Ca/Mg ratios in this study (Figure 4-34). The relationship can be described by a power function:

$$Y=1.5348X^{0.3805}-0.5704 \quad (r^2=0.9424, P<0.001, n=42) \quad \ldots\ldots\ldots\ldots \quad [6]$$

Where Y is the plant Ca/Mg ratio and X is the soil Ca/Mg ratio. In this study, the plant Ca/Mg ratio reflected the soil Ca/Mg ratio. Plant nutrient concentration ratios have been used to indicate plant nutrient balance and as a method for diagnosing plant nutrient status in the Diagnosis and Recommendation Integrated System (DRIS) developed by Beaufils (1973)and applied in many field crops as a useful way to evaluate the nutrient status of plants as reviewed by Walworth and Sumner (1987, 1988).

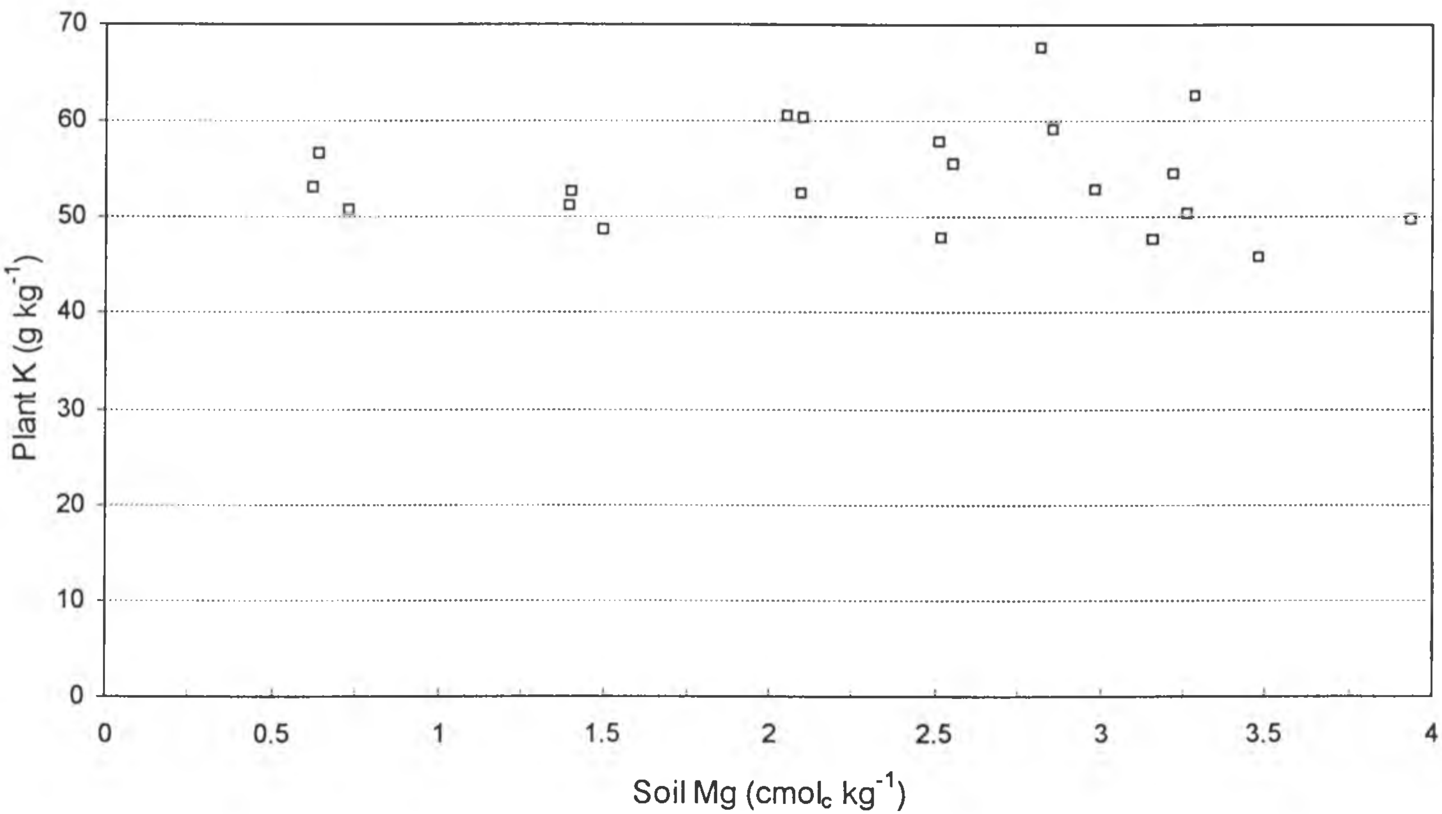

Figure 4-32. The relationship between soil Mg and plant K in lettuce

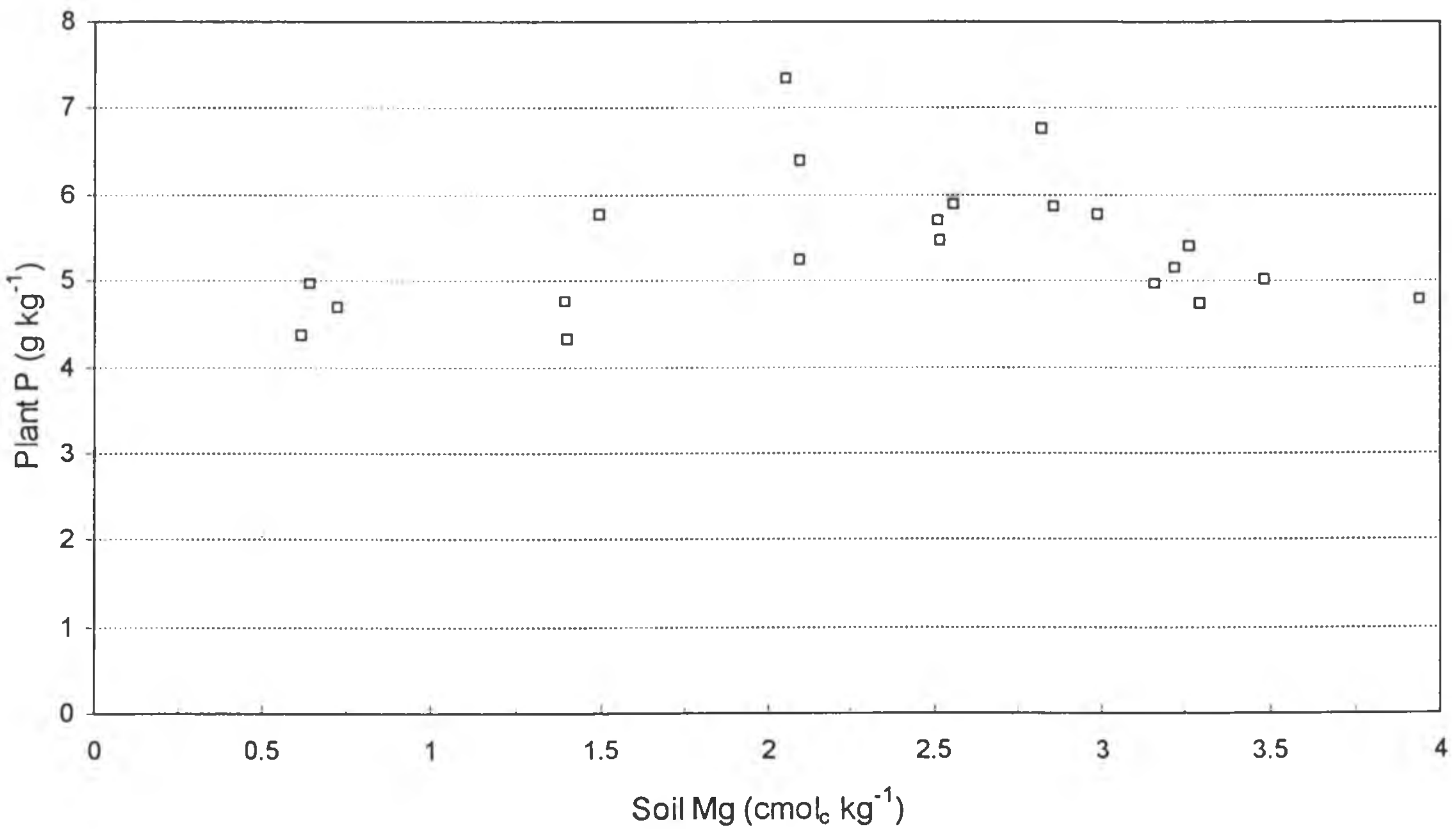

Figure 4-33 The relationship between soil Mg and plant P in lettuce

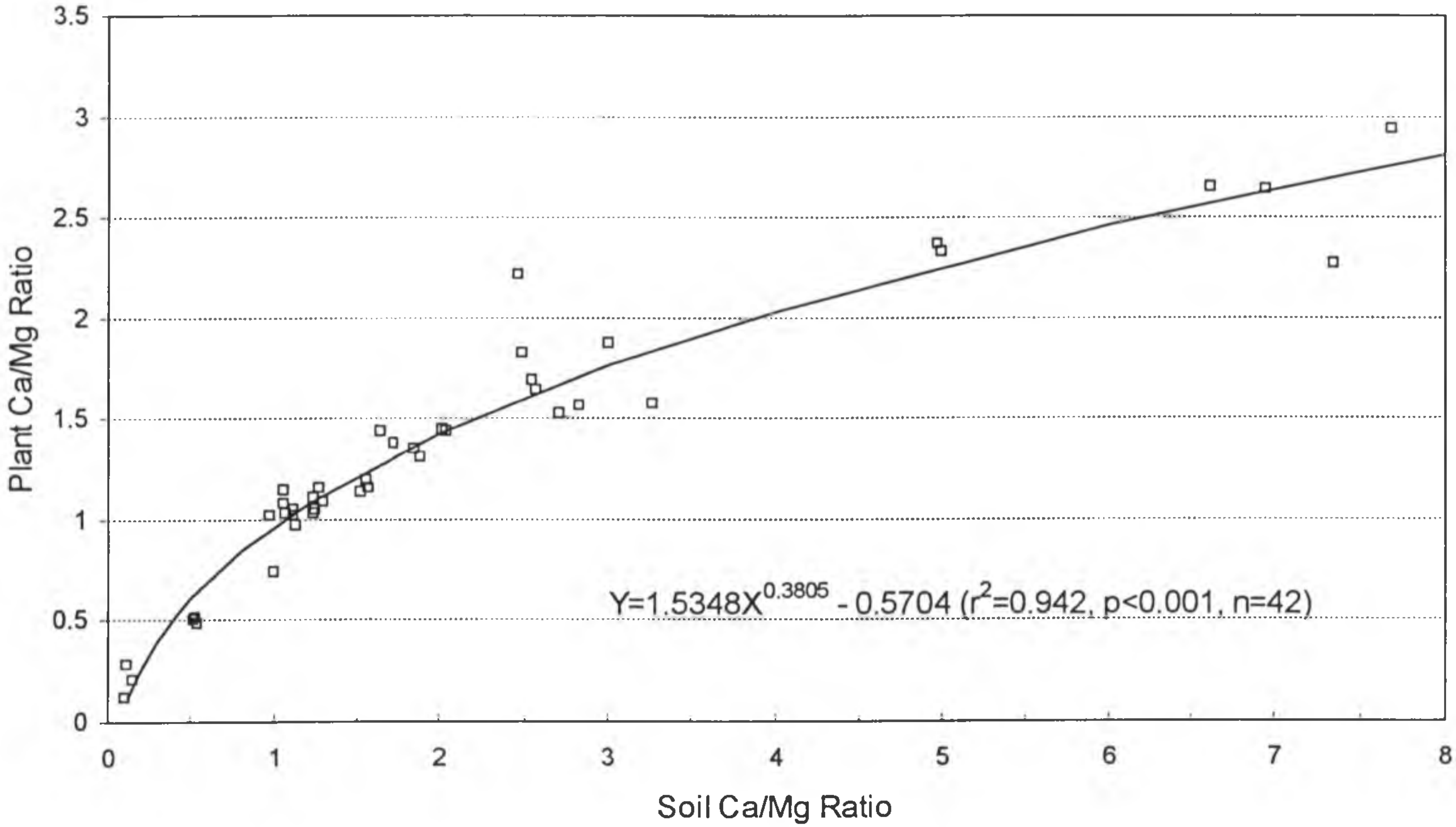

Figure 4-34. The relationship between soil Ca/Mg ratios and plant Ca/Mg ratios in lettuce

CHAPTER 5

SUMMARY AND CONCLUSIONS

Ca Experiment

Lettuce made little growth when grown on an acid Ultisol (Manana soil series) with a soil Ca level at 0.57 $cmol_c\ kg^{-1}$. Application of increasing amounts of $CaSO_4$ from 1000 kg ha^{-1} to 6000 kg ha^{-1} increased soil Ca to about 1.92 $cmol_c\ kg^{-1}$ to 7.16 $cmol_c\ kg^{-1}$ after leaching of 5 liter de-ionized water, which resulted in normal growth of lettuce and produced significantly more dry matter than the zero Ca treatment. Lettuce in the zero Ca treatment exhibited Ca deficiency symptoms in the Ca experiment. A yield response curve was fitted by a ratio function:

$$Y=0.23553-0.07156/X^2\ (r^2=0.659,\ P<0.001,\ n=21)\ \ldots\ldots\ldots\ldots\ldots\quad [1]$$

Where Y is yield (dry matter) and X is soil Ca. Soil Mg as a co-varying factor had no significant effect on yield response. Similarly, the relationship between yield and plant Ca level can be expressed by a quadratic function:

$$Y=0.06075X-0.003019X^2-0.0489\ (r^2=0.564,\ P<0.001,\ n=21)\quad \ldots\ldots\quad [3]$$

Where Y is yield (dry matter) and X is plant Ca level.

The critical soil Ca level found in the literature ranges from 1 to 3 $cmol_c\ kg^{-1}$ depending on the soil, crop and other conditions. The critical soil Ca level for lettuce on the Manana soil series determined by the Cate-Nelson method was 1.9 $cmol_c\ kg^{-1}$. This critical level is more reasonable and lower than the 5 $cmol_c\ kg^{-1}$ that is currently recommended in Hawaii. The critical plant Ca concentration for lettuce in the literature ranged from 4.3~13 g kg^{-1} depending on the plant part sampled, crop age and other conditions. A critical plant Ca concentration for lettuce at maturity on the Manana soil series was determined to be 4 g kg^{-1} by the Cate-Nelson method. It is interesting to note that plant Ca reflects the level of available soil Ca. Both soil and plant critical levels can be determined when a crop responds to increasing levels of a nutrient.

Exchangeable soil cations interact with each other and application of a large amount of liming material can cause cation imbalance. In the Ca experiment, soil Mg decreased when soil Ca increased. There was a high correlation between them ($r=-0.871$, $P<0.001$, $n=21$). Similarly, soil K decreased with an increase of soil Ca. The correlation between them was also high ($r=-0.835$, $P<0.001$, $n=21$). Moreover, soil Na followed the same pattern as soil Mg and K and its decrease was very highly correlated ($r=-0.924$, $P<0.001$, $n=21$) with an increase of soil Ca. When large amounts of one cation are applied to soil, the other cations will decrease as the soil solution is leached out of the profile.

In the Ca experiment, plant uptake of Ca was very highly, positively related to soil Ca level. The relationship was linear with $r=0.970$ ($P<0.001$, $n=21$). Plant Mg uptake, on the other hand, decreased as soil Ca level increased. The effect of soil Ca on plant Mg was indirect because the Ca increase caused a decrease of soil Mg and the decrease in soil Mg reduced plant uptake of Mg. The negative correlation of soil Ca with plant Mg was significant ($r=-0.747$, $P<0.001$, $n=21$). Plant uptake of Na was also reduced as a result of a decrease of soil Na levels, which was caused by the increase in soil Ca. The negative correlation of soil Ca with plant Na was also significant ($r=-0.869$, $P<0.001$, $n=21$). However, although soil K levels were reduced by the increase in soil Ca, plant K uptake did not appear to be linearly related to the decrease of soil K. Potassium uptake was reduced by low soil Ca due to decreased ion selectivity and leakiness of membranes which occurred when Ca was deficient. When soil Ca was adequate, the relationship was linear. Therefore, a quadratic function was fitted to describe the relationship between soil Ca level and plant K uptake:

$$Y= 56.99-1.781X-11.02/X^2 \ (r^2=0.833, P<0.01, n=21) \qquad \ldots\ldots\ldots\ldots\ldots \quad [5]$$

Where Y is plant K level and X is soil Ca level. It is very interesting to observe this plant K uptake phenomenon which provided evidence of the importance of Ca in plant nutrition. Moreover, soil Ca appeared to have no effect on soil P or plant P.

Mg Experiment

Lettuce did not respond to increased levels of soil Mg on the Manana soil series with a soil Mg level at 0.67 $cmol_c\ kg^{-1}$. The growth of lettuce was normal with all soil Mg levels. Lettuce in the zero Mg treatment did not show any Mg deficiency symptoms. There was no significant relationship between lettuce yield and soil Mg level. Soil Ca and the soil Ca/Mg ratio as co-varying factors had no significant effects on yield response. Similarly, there was no significant relationship between lettuce yield and plant Mg level.

The critical soil Mg level found in the literature ranges from 0.06 to 0.6 $cmol_c\ kg^{-1}$ depending on the soils, crops and other conditions. A critical soil Mg level for lettuce on the Manana soil series could not be established in this study because there was no yield response to Mg applications, but it appears that the soil Mg level of the zero Mg treatment, 0.67 $cmol_c\ kg^{-1}$ or above is adequate for lettuce. Therefore, the sufficiency range for soil Mg used in Hawaii (2.5 to 3.3 $cmol_c\ kg^{-1}$) appears to be too high based on the findings of this study.

The critical plant Mg concentration for lettuce in the literature ranged from 3~5 g kg^{-1} depending on the plant part sampled, crop age and other conditions. A critical plant Mg concentration for lettuce at maturity on the Manana soil series could not be determined in this study because there was no crop response to increased levels of soil Mg. However, plant Mg of 4 g kg^{-1} or above appears to be adequate for lettuce growth. It is also interesting to note that plant Mg nutrient concentration reflects the levels of available soil Mg.

More evidence was found in the Mg experiment for the relationships between soil cations. Soil Ca decreased significantly when soil Mg increased ($r=-0.633$, $P<0.01$, $n=21$). Similarly, soil K decreased with the increase of soil Mg with a correlation coefficient of $r=-0.637$, $P<0.01$, $n=21$. Moreover, soil Na followed the same pattern as soil Ca and K and its decrease was highly correlated ($r=-0.912$, $P<0.001$, $n=21$) with the increase of soil Mg. Since the soil Ca level is low in the Manana soil series, the application of Mg based lime instead of Ca based lime caused Ca deficiency in plants grown on the zero Ca treatment. Therefore, adequate soil Ca or Mg nutrient levels as well as Ca and Mg balance must be considered in liming acid tropical soils to avoid Ca or Mg deficiency caused by low Ca or Mg level that may be further enhanced by Ca or Mg imbalance.

Plant uptake of Mg was positively related to soil Mg levels in the Mg experiment. The relationship between soil Mg and plant uptake of Mg was also linear with $r=0.723$ ($P<0.001$, $n=21$). Plant Ca uptake, on the other hand, decreased as soil Mg level increased. This is an indirect effect because the increase of soil Mg caused a decrease of soil Ca available for plant uptake following leaching. The correlation between soil Mg and plant uptake of Ca was significant ($r=-0.854$, $P<0.001$, $n=21$). Plant uptake of Na was also reduced as a result of a decrease in soil Na levels, which was caused by the increase in soil Mg. A correlation coefficient of -0.843 was found for the relationship ($P<0.001$, $n=21$). Although soil K levels were also reduced by the increase in soil Mg, plant K uptake did not appear to be affected. The same plant K uptake phenomena found in the Ca experiment was found in the Mg experiment. There was no significant inverse relationship between soil Mg levels and plant K uptake. Moreover, there was no correlation between soil Mg levels and plant P uptake.

Ca/Mg ratio

In the range of soil Ca/Mg ratios from 0.11 to 7.7 expressed on the basis of cmol kg^{-1} on the Manana soil series in this study, lettuce growth decreased only at extremely low Ca/Mg ratios, i.e., around 0.11. No yield reduction was observed in the range of soil Ca/Mg from 0.5 to 7.7, which is within the optimal Ca/Mg ratio range considered by most studies reported in the literature. This study provides more evidence for the conclusion that plants can grow normally with a broad range of Ca/Mg ratios. No information about high soil Ca/Mg ratios was obtained in this study because the highest Ca/Mg ratio was only 7.7 which is well within the optimal range. The relationship between lettuce yield and soil Ca/Mg ratio can be described by a ratio function:

$$Y = 0.2871 - 0.0328/X \quad (r^2=0.402,\ P< 0.001,\ n=42) \ldots\ldots\ldots\ldots \quad [2]$$

Where Y is yield (dry matter) and X is soil Ca/Mg ratio. However, since soil Ca and Mg were co-varying with the Ca/Mg ratio, stepwise regression was used to investigate relationships between them. It indicated that the main effects of these co-varying factors were soil Ca and the Ca/Mg ratio in the Ca experiment. The yield response to soil Ca/Mg ratios must be interpreted with caution because co-varying factors may also affect the relationships. The relationship between lettuce yield and plant Ca/Mg ratio can also be described by a ratio function:

$$Y=0.2978-0.04215/X \ (r^2=0.355, P<0.001, n=42) \quad \ldots\ldots\ldots\ldots \quad [4]$$

Where Y is yield (dry matter) and X is plant Ca/Mg ratio.

The lower soil Ca/Mg ratio critical level was determined as 0.5 on the basis of $cmol_c \ kg^{-1}$ in the literature. A lower critical level of soil Ca/Mg ratio for lettuce on the Manana soil series was determined by the Cate-Nelson method to be 0.5. Below this critical level, serious yield reductions are likely to occur due to Ca deficiency and other nutrient problems caused by imbalance between Ca and Mg. It should also be pointed out that the critical soil Ca/Mg ratio should be used along with soil Ca or Mg levels for liming and fertilizer recommendations since co-varying effects may exist. No critical level of plant Ca/Mg concentration ratio of lettuce was found in the literature. In this study, a critical plant Ca/Mg concentration ratio for lettuce at maturity on the Manana soil series was determined to be 0.5 by the Cate-Nelson method. Similar to the soil Ca/Mg ratio, the plant Ca/Mg nutrient concentration ratio can also be an indicator of plant nutrient status. In fact, plant nutrient concentration ratios have been used as a method for diagnosing plant nutrient status.

Plant Ca/Mg ratios in lettuce were significantly affected by soil Ca/Mg ratios in this study. The relationship can be described by a power function:

$$Y=1.5348X^{0.3805}-0.5704 \ (r^2=0.942, P<0.001, n=42) \quad \ldots\ldots\ldots\ldots \quad [6]$$

Where Y is the plant Ca/Mg ratio and X is the soil Ca/Mg ratio.

Appendix A. Fertilizer Treatments of the Ca and Mg Experiments

Treatment Design:

Treatment		$Ca(OH)_2$ (Ca,kg ha^{-1})	$Mg(OH)_2$ (Mg,kg ha^{-1})	$CaSO_4$ (Ca,kg ha^{-1})	$MgSO_4$ (Mg,kg ha^{-1})
Ca experiment	Ca1	0	1200	0	0
	Ca2	0	1200	1000	0
	Ca3	0	1200	2000	0
	Ca4	0	1200	3000	0
	Ca5	0	1200	4000	0
	Ca6	0	1200	5000	0
	Ca7	0	1200	6000	0
Mg experiment	Mg1	2000	0	0	0
	Mg2	2000	0	0	250
	Mg3	2000	0	0	500
	Mg4	2000	0	0	750
	Mg5	2000	0	0	1000
	Mg6	2000	0	0	1250
	Mg7	2000	0	0	1500

Fertilizer Dose:

Treatment		$Ca(OH)_2$	$Mg(OH)_2$	$CaSO_4$	$MgSO_4 \cdot 7H_2O$	$(NH_4)_2HPO_4$	KH_2PO_4	$NaH_2PO_4 \cdot H_2O$
					g/pot			
Dry matter (%)		97.2	98	98	100	99.8	99.6	99.5
Ca experiment	Ca1	0.000	2.883	0.000	0.000	1.288	0.955	2.956
	Ca2	0.000	2.883	3.380	0.000	1.288	0.955	2.956
	Ca3	0.000	2.883	6.759	0.000	1.288	0.955	2.956
	Ca4	0.000	2.883	10.139	0.000	1.288	0.955	2.956
	Ca5	0.000	2.883	13.518	0.000	1.288	0.955	2.956
	Ca6	0.000	2.883	16.898	0.000	1.288	0.955	2.956
	Ca7	0.000	2.883	20.277	0.000	1.288	0.955	2.956
Mg experiment	Mg1	3.713	0.000	0.000	0.000	1.288	0.955	2.956
	Mg2	3.713	0.000	0.000	2.501	1.288	0.955	2.956
	Mg3	3.713	0.000	0.000	5.002	1.288	0.955	2.956
	Mg4	3.713	0.000	0.000	7.504	1.288	0.955	2.956
	Mg5	3.713	0.000	0.000	10.005	1.288	0.955	2.956
	Mg6	3.713	0.000	0.000	12.506	1.288	0.955	2.956
	Mg7	3.713	0.000	0.000	15.007	1.288	0.955	2.956
Total		77.973	60.533	212.910	157.576	54.112	40.108	124.138

Treatments were replicated 3 times
Soil dry matter = 97.41%

APPENDIX B. Soil Analysis for Treatments before and after leaching in Ca and Mg Experiments

Treatment		Soil Ca		Soil Mg		Soil Na		Soil K		Total Cations		Ca/Mg Ratio		Soil pH		EC	
		Before*	After	Before*	After	Before*	After	Before*	After	Before	After	Before	After	Before	After	Before	After
		....		....		$cmol_c\ kg^{-1}$		....		....		$cmol_c\ kg^{-1}$basis		1:1 H_2O		$dS\ m^{-1}$	
Ca experiment	Ca1	0.565	0.565	5.667	4.492	1.909	1.404	0.446	0.538	8.587	6.999	0.100	0.126	5.50	6.00	0.764	0.691
	Ca2	3.065	1.915	5.667	3.625	1.909	0.996	0.446	0.513	11.087	7.048	0.541	0.528	5.30	5.75	2.327	0.618
	Ca3	5.565	3.560	5.667	3.192	1.909	0.704	0.446	0.441	13.587	7.897	0.982	1.114	5.00	5.80	2.727	0.873
	Ca4	8.065	3.810	5.667	2.317	1.909	0.604	0.446	0.390	16.087	7.121	1.423	1.646	4.90	5.50	5.636	0.945
	Ca5	10.565	5.035	5.667	2.075	1.909	0.496	0.446	0.315	18.587	7.921	1.864	2.422	4.90	5.50	7.309	1.345
	Ca6	13.065	5.510	5.667	2.067	1.909	0.465	0.446	0.362	21.087	8.403	2.306	2.663	5.10	5.55	6.145	1.018
	Ca7	15.565	7.160	5.667	1.292	1.909	0.391	0.446	0.341	23.587	9.184	2.747	5.549	4.95	5.15	9.491	2.873
Mg experiment	Mg1	5.565	4.780	0.667	0.667	1.909	1.265	0.446	0.610	8.587	7.322	8.348	7.191	5.30	5.90	0.727	0.582
	Mg2	5.565	4.155	1.708	1.433	1.909	1.170	0.446	0.531	9.628	7.289	3.258	2.902	5.20	5.80	1.091	0.691
	Mg3	5.565	4.005	2.750	2.083	1.909	1.035	0.446	0.579	10.670	7.703	2.024	1.921	5.30	5.80	2.109	0.8
	Mg4	5.565	3.685	3.792	2.525	1.909	0.961	0.446	0.487	11.712	7.658	1.468	1.457	5.20	5.65	2.473	0.8
	Mg5	5.565	3.835	4.833	3.158	1.909	0.935	0.446	0.526	12.753	8.454	1.151	1.215	5.15	5.80	3.382	0.909
	Mg6	5.565	3.715	5.875	3.350	1.909	0.726	0.446	0.459	13.795	8.250	0.947	1.107	5.15	5.70	3.418	0.873
	Mg7	5.565	3.425	6.917	3.167	1.909	0.765	0.446	0.474	14.837	7.831	0.805	1.082	5.10	5.65	3.055	0.764

* Soil Ca, Mg, K and Na before leaching are calculated from the amount added and the amount in soil

Appendix C. Experimental Results of the Ca and Mg Experiments

Treat	Dose	Rep	Soil Ca	Soil Mg	Soil Na	Soil K	Soil Ca/Mg	Plant Ca	Plant Mg	Plant Na	Plant K	Plant P	Plant Ca/Mg	Dry Wt	Dry Wt
	kg ha^{-1}		———	$cmol_c\ kg^{-1}$		———		———		$g\ kg^{-1}$		———		g/plant	g/pot
Ca1	0	1	0.577	5.230	1.263	0.488	0.11	1.067	9.148	26.282	22.892	6.618	0.12	0.010	0.058
Ca2	1000	1	1.856	3.443	0.952	0.497	0.54	5.056	10.510	24.019	57.548	6.268	0.48	0.193	1.156
Ca3	2000	1	4.286	3.470	0.673	0.425	1.24	6.936	6.763	15.923	46.262	5.039	1.03	0.226	1.356
Ca4	3000	1	3.760	2.173	0.657	0.402	1.73	8.682	6.317	14.960	45.186	5.420	1.37	0.243	1.456
Ca5	4000	1	5.902	2.173	0.443	0.244	2.72	12.080	7.915	19.046	38.083	5.875	1.53	0.153	0.916
Ca6	5000	1	5.668	1.883	0.434	0.319	3.01	10.450	5.575	13.591	47.732	5.484	1.87	0.213	1.277
Ca7	6000	1	7.758	1.117	0.365	0.307	6.94	16.556	6.268	12.106	52.383	6.037	2.64	0.158	0.945
Ca1	0	2	0.543	4.470	1.505	0.495	0.12	2.448	8.652	31.078	22.805	5.022	0.28	0.010	0.052
Ca2	1000	2	1.893	3.657	1.039	0.482	0.52	4.262	8.414	20.624	56.104	5.593	0.51	0.215	1.292
Ca3	2000	2	2.460	2.436	0.820	0.446	1.01	7.155	9.649	18.909	54.074	6.615	0.74	0.080	0.478
Ca4	3000	2	3.650	2.316	0.540	0.373	1.58	7.764	6.714	15.851	44.325	5.864	1.16	0.264	1.582
Ca5	4000	2	4.942	1.983	0.456	0.310	2.49	9.817	5.394	15.983	45.511	5.310	1.82	0.300	1.799
Ca6	5000	2	5.324	2.083	0.466	0.347	2.56	11.266	6.684	17.457	47.933	6.426	1.69	0.265	1.588
Ca7	6000	2	6.018	1.211	0.405	0.366	4.97	13.199	5.574	12.171	47.121	5.427	2.37	0.187	1.121
Ca1	0	3	0.572	3.787	1.441	0.629	0.15	1.803	8.899	29.911	16.787	6.422	0.20	0.008	0.049
Ca2	1000	3	2.002	3.783	1.002	0.559	0.53	4.701	9.208	23.794	49.857	6.174	0.51	0.310	1.862
Ca3	2000	3	3.930	3.680	0.626	0.454	1.07	6.420	5.619	14.916	44.800	4.842	1.14	0.277	1.660
Ca4	3000	3	4.020	2.456	0.616	0.393	1.64	8.453	5.881	17.296	47.879	5.347	1.44	0.274	1.641
Ca5	4000	3	4.264	2.082	0.586	0.392	2.05	10.281	7.189	16.699	51.903	5.456	1.43	0.197	1.182
Ca6	5000	3	5.542	2.242	0.501	0.416	2.47	10.843	4.912	14.882	45.197	4.440	2.21	0.311	1.868
Ca7	6000	3	7.704	1.543	0.400	0.351	4.99	13.920	5.988	13.327	43.515	4.963	2.32	0.265	1.588
Mg1	0	1	4.784	0.622	1.234	0.583	7.70	11.526	3.918	21.086	52.905	4.355	2.94	0.276	1.380
Mg2	250	1	3.966	1.400	1.139	0.480	2.83	9.024	5.771	21.328	52.614	4.318	1.56	0.250	1.252
Mg3	500	1	3.894	2.056	1.054	0.568	1.89	9.985	7.610	20.356	60.433	7.341	1.31	0.200	0.999
Mg4	750	1	3.312	2.555	0.976	0.501	1.30	9.364	8.661	21.577	55.531	5.885	1.08	0.220	1.099
Mg5	1000	1	4.438	3.483	0.736	0.434	1.27	7.605	6.579	16.778	45.667	4.996	1.16	0.470	2.352
Mg6	1250	1	3.874	3.940	0.614	0.477	0.98	6.829	6.702	16.236	49.688	4.767	1.02	0.378	1.892
Mg7	1500	1	3.408	3.220	0.643	0.413	1.06	7.841	7.302	16.223	54.330	5.134	1.07	0.334	1.672
Mg1	0	2	4.828	0.729	1.321	0.619	6.62	11.105	4.196	23.456	50.679	4.682	2.65	0.342	1.712
Mg2	250	2	3.592	1.395	1.170	0.584	2.58	9.103	5.546	21.340	51.124	4.752	1.64	0.228	1.142
Mg3	500	2	4.234	2.100	1.030	0.560	2.02	7.329	5.089	20.392	52.340	5.243	1.44	0.369	1.845
Mg4	750	2	3.920	2.518	0.934	0.441	1.56	7.430	6.253	19.920	47.771	5.472	1.19	0.309	1.543
Mg5	1000	2	3.904	3.160	0.961	0.536	1.24	6.718	6.083	18.527	47.508	4.960	1.10	0.473	2.366
Mg6	1250	2	3.568	2.858	0.752	0.416	1.25	7.378	7.020	17.262	58.988	5.862	1.05	0.296	1.482
Mg7	1500	2	3.336	2.984	0.828	0.478	1.12	7.197	6.881	18.003	52.797	5.769	1.05	0.277	1.383
Mg1	0	3	4.722	0.642	1.238	0.628	7.35	10.822	4.763	23.392	56.433	4.964	2.27	0.254	1.271
Mg2	250	3	4.900	1.499	1.194	0.527	3.27	9.595	6.119	25.238	48.602	5.772	1.57	0.377	1.886
Mg3	500	3	3.892	2.100	1.020	0.607	1.85	9.444	7.010	19.948	60.285	6.396	1.35	0.249	1.246
Mg4	750	3	3.822	2.513	0.966	0.518	1.52	7.556	6.663	19.531	57.647	5.699	1.13	0.269	1.347
Mg5	1000	3	3.156	2.821	1.113	0.610	1.12	6.852	6.714	18.955	67.410	6.745	1.02	0.170	0.850
Mg6	1250	3	3.696	3.263	0.813	0.486	1.13	8.032	8.298	19.645	50.269	5.386	0.97	0.220	1.102
Mg7	1500	3	3.526	3.290	0.829	0.535	1.07	7.958	7.722	17.894	62.424	4.721	1.03	0.291	1.455

APPENDIX D. Regression Analysis

X	Y	Relationship	r^2	p	n	Equation No.
Relationships between lettuce yield and soil Ca, Mg and the Ca/Mg ratio						
Soil Ca	Yield	$Y=0.2355-0.07156/X^2$	0.6593	<0.001	21	1
Soil Mg	Yield	$Y=0.2725+0.00007026X^{5.554}$	0.1782	>0.05	21	
Soil Ca/Mg	Yield	$Y=0.2871-0.03280/X$	0.4018	<0.001	42	2
Soil Ca	Plant K	$Y= 56.99-1.781X-11.02/X^2$	0.8330	<0.001	21	5
Relationships between lettuce yield and plant Ca, Mg and the Ca/Mg ratio						
Plant Ca	Yield	$Y=0.06075X-0.003019X^2-0.04891$	0.5635	<0.001	21	3
Plant Mg	Yield	$Y=1.5653X-0.013886X^2-0.1143$	0.1632	>0.05	21	
Plant Ca/Mg	Yield	$Y=0.2978-0.04215/X$	0.3547	<0.001	42	4
Relationships between soil Ca/Mg ratios and plant Ca/Mg ratios						
Soil Ca/Mg	Plant Ca/Mg	$Y=1.5348X^{0.3805}-0.5704$	0.9424	<0.001	42	6

APPENDIX E. Stepwise Regression Analysis

	X_1	X_2	X_3	Y	Relationship	r^2	p	n
Ca Experiment								
Variable	Soil Ca	Soil Mg	Soil Ca/Mg	Yield	$Y=0.04478+0.07240X_1-0.06528X_3$	0.5316	<0.01	21
In Model	Yes	No	Yes					
P value	0.0005	0.4791	0.0057					
Mg Experiment								
Variable	Soil Ca	Soil Mg	Soil Ca/Mg	Yield				21
In Model	No	No	No					
P value	0.0614	0.2334	0.7849					

APPENDIX F. Correlation Analysis

X	Y	Relationship	r	p	n
Relationships between soil Ca and other cations					
Soil Ca	Soil Mg	Y=4.451-0.4385X	-0.8707	<0.001	21
Soil Ca	Soil K	Y=0.5526-0.03517X	-0.8346	<0.001	21
Soil Ca	Soil Na	Y=1.306-0.1480X	-0.9244	<0.001	21
Relationships between soil Mg and other cations					
Soil Mg	Soil Ca	Y=4.737-0.3400X	-0.6329	<0.01	21
Soil Mg	Soil K	Y=0.6269-0.04403X	-0.6368	<0.01	21
Soil Mg	Soil Na	Y=1.420-0.1882X	-0.9121	<0.001	21
Relationships between soil Ca and plant nutrient uptake					
Soil Ca	Plant Ca	Y=1.000+1.841X	0.9701	<0.001	21
Soil Ca	Plant Mg	Y=9.420-0.5630X	-0.7471	<0.001	21
Soil Ca	Plant Na	Y=27.21-2.207X	-0.8694	<0.001	21
Soil Ca	Plant P	Y=6.078-0.1088X	-0.3809	>0.05	21
Relationships between soil Mg and plant nutrient uptake					
Soil Mg	Plant Mg	Y=4.282+0.9151X	0.7231	<0.001	21
Soil Mg	Plant Ca	Y=11.53-1.289X	-0.8535	<0.001	21
Soil Mg	Plant Na	Y=24.72-2.074X	-0.8426	<0.001	21
Soil Mg	Plant K	Y=54.08-0.00339X	-0.0006	>0.05	21
Soil Mg	Plant P	Y=5.047+0.1470X	0.1852	>0.05	21

LITERATURE CITED

Analytical Software, 1991: Statistix 3.5: An Interactive Statistical Analysis Program for the IBM PC. Analytical Software.

Adams, F. 1975. Field experiments with magnesium in Alabama - cotton, corn, soybeans, peanuts. Alabama Agric. Exp. Stn. Bull. 472.

Adams, F. 1978. Liming and fertilization of ultisoils and oxisoils. In C.S. Andrew and E.J. Kamprath (ed.) Mineral nutrition of legumes in tropical and subtropical soils. p. 377-394. CSIRO, East Melbourne, Australia.

Adams, F. 1981. Nutritional imbalances and constraints to plant growth in acid soils. J. Plant Nutr. 4:81-87.

Adams, F. 1984. Crop response to lime in the Southern United States. In F. Adams (ed.) Soil acidity and liming, 2nd ed. Agronomy 12:211-265. ASA, CSSA, and SSSA, Madison, WI.

Adams, F. and J.B. Henderson. 1962. Magnesium availability as affected by deficient and adequate levels of potassium and lime. Soil Sci Soc. Am. Proc. 26:65-68.

Andrew, C.S., and D.O. Norris. 1961. Comparative responses to calcium of five tropical and four temperate pasture legume species. Aust. J. Agric. res. 12:40-50.

Baize, D. 1993. Soil science analyses: A guide to current use. Wiley, Chichester.

Bear, F.E., A.L. Prince, and J.C. Malcolm. 1945. The potassium needs of New Jersey soils. New Jersey Agric. Stn. Bull. 721.

Bear, F.E. and S.J. Toth. 1948. Influence of calcium on other soil cations. Soil Sci. 65:69-75.

Beaufils, E.R. 1973. Diagnosis and recommendation integrated system (DRIS): A general scheme for experimentation and calibration based on principles developed from research in plant nutrition. University of Natal, Soil Science Bulletin 1.

Bray, R.H. 1944. Soil-plant relationships: I. The quantitative relation of exchangeable K to crop yields and to crop response to potash additions. Soil Sci. 58:305-324.

Bray, R.H. 1945. Soil-plant relationships: II. Balanced fertilizer use through soil tests for K and P. Soil Sci. 60:463-473.

Cate, R.B. Jr., and L.A. Nelson. 1965. A rapid method for correlation of soil test analyses with plant response data. North Carolina Agric. Exp. Stn. International Soil Testing Series Tech. Bull. No. 1.

Cate, R.B. Jr., and L.A. Nelson. 1971. A simple statistical procedure for partitioning soil test correlation data into two classes. Soil Sci. Soc. Am. Proc. 35:658-660.

Chan, K.Y., B.G. Davey, and H.R. Geering. 1979. Adsorption of magnesium and calcium by soil with variable charge. Soil Sci. Soc. Am. J. 43:301-304.

Clark, R.B. 1982. Plant response to mineral element toxicity and deficiency. In M. N. Christiansen and C.F. Lewis (ed.) Breeding plants for less favorable environments. p. 71-142. John Wiley & Sons, Inc., New York.

Clark, R.B. 1984. Physiological aspects of calcium, magnesium, and molybdenum deficiencies in plants. In F. Adams (ed.) Soil acidity and liming, 2nd ed. Agronomy 12:99-170. ASA, CSSA, and SSSA, Madison, WI.

Cochrane, T.T. 1989. Chemical properties of native savannas and forest soils in Central Brazil. Soil Sci. Soc. Am. J. 53:139-141.

Cox, F.R., F. Adams, and B.B. Tucker. 1982. Liming, fertilization, and mineral nutrition. In H.E. Pattee and C.T. Young (ed.) Peanut science and technology. P. 139-163. North Carolina State Univ., Raleigh.

Dahnke, W.C., and R.A. Olson. 1990. Soil test correlation, calibration, and recommendation. In R.L. Westerman (ed.) Soil testing and plant analysis. 3rd ed. p. 49-71. SSSA, Madison, Wisconsin.

Dept of Agronomy and Soil Science, 1993. Waiawa project. Dept of Agronomy and Soil Science, Univ. of Hawaii at Manoa.

Doll, E.C., and R.E. Lucas. 1973. Testing soils for potassium, calcium, and magnesium. In L.M. Walsh and J.D. Beaton (ed.) Soil testing and plant analysis. p. 133-151. SSSA, Madison, Wisconsin.

Eckert, D.J., 1987. Soil test interpretations: Basic cation saturation ratios and sufficiency levels. In J.R. Brown (ed.) Soil Testing: Sampling, Correlation, Calibration, and Interpretation. SSSA Special Publication #21. SSSA, Inc., Madison, Wisconsin.

Eckert, D.J. and E.O. McLean. 1981. Basic cation saturation ratios as a basis for fertilizing and liming agronomic crops. I. Growth chamber studies. Agron. J. 73:795-799.

Food and Agriculture Organization, UN, 1958. Efficient use of fertilizers. FAO, UN.

Farina, M.P.W., M.E. Sumner, C.O. Plank, and W.S. Letzsch. 1980. Effect of pH on soil magnesium and its absorption by corn. Commun. Soil Sci. Plant Anal. 11:981-992.

Foy, C.D., R.L. Chaney, and M.C. White. 1978. The physiology of metal toxicity in plants. Ann. Rev. Plant Physiol. 29:511-566.

Foy, C.D. 1984. Physiological effects of Hydrogen, aluminum, and manganese toxicities in acid soil. In F. Adams (ed.) Soil acidity and liming, 2nd ed. Agronomy 12:57-97. ASA, CSSA, and SSSA, Madison, WI.

Fox, R.H., and W.P. Piekielek. 1984. Soil magnesium level, corn (*Zea mays L.*) yield, and magnesium uptake. Commun. Soil Sci. Plant Anal. 15:109-123.

Franklin, W.T., J.S. Olsen and P.N. Soltanpour. 1991. Effects of excessive magnesium in irrigation waters on wheat and corn growth. Commun. Soil Sci. Plant Anal. 22(1&2):49-61.

Fitts, J.W. 1955. Using soil tests to predict a probable response to fertilizer application. Better Crops Plant Food. 39:17-20.

Fitts, J.W., and W.L. 1956. The determination of lime and fertilizer requirements of soils through chemical tests. In A.G. Norman (ed.) Adv. In Agronomy. Vol 8. Academic Press, New York.

Geralson, C.M. 1954. The control of blackheart of celery. Proc. Am. Soc. Hortic. Sci. 63:353-358.

Geralson, C.M. 1957. Control of blossom-end rot of tomatoes. Proc. Am. Soc. Hortic. Sci. 69:309-317.

Giddens, J., and S.J. Toth. 1951. Growth and nutrient uptake of ladino clover growth on red and yellow and grey-brown Podzolic soils containing varying ratios of cations. Agron. J. 43:209-214.

Gong, Z.T. et al., 1981. Subtropical soils in Central China. Hunan Sci. & Tech. Publishers, Hunan, China.

Graham, E.R. 1959. An explanation of the theory and methods of soil testing. Missouri Agric. Exp Stn. Bull. 734.

Grant, C.A. and L.D. Bailey. 1990. The effect of magnesium sulphate and calcium sulphate on yield and nutrient composition of flax (*Linum ustassimum*) grown on chernozemic soils. In Van Beusichem (ed.) Plant nutrition: physiology and applications. Kluwer Academic Publishers, Dordrecht.

Grove, J.H., and M.E. Sumner. 1985. Lime induced magnesium stress in corn: Impact on magnesium and phosphorus availability. Soil Sci. Soc. Am. J. 49:1192-1196.

Grove, J.H., M.E. Sumner, and J.K. Syers. 1981. Effect of lime on exchangeable magnesium in variable surface soils. Soil Sci. Soc. Am. J. 45:497-500.

Haby, V.A., M.P. Russelle, and E.O. Skogley. 1990. Testing soils for potassium, calcium, and magnesium. In R.L. Westerman (ed.) Soil testing and plant analysis. 3rd ed. p. 181-227. SSSA, Madison, Wisconsin.

Halstead, R.L., A.J. MacLean, and K.F. Nielsen. 1958. Ca:Mg ratios in soil and the yield and composition of alfalfa. Can J. Soil Sci. 38:85-92.

Hendershot, W.H., H. Lalande, and M. Duquette, 1993. Ion exchange and exchangeable cations. In Carter (ed.) Soil Sampling and Methods of Analysis. P. 167-176. Lewis. Boca Raton.

Hunter, A.S. 1949. Yield and composition of alfalfa as affected by variations in calcium-magnesium ratio in the soil. Soil Sci. 67:53-62.

Hunter, A.S., S.J. Toth, and F.E. Bear. 1943. Calcium-potassium ratios for alfalfa. Soil Sci. 55:61-72.

Hunter, D.J., L.G.G. Yapa, N.V. Hue, and M. Eaqub. 1995. Comparative effects of green manure and lime on the growth of sweet corn and chemical properties of an acid Oxisol in Western Samoa. Commun. Soil Sci. Plant Anal. 26(3&4):375-388.

Jacson, W.A. 1967. Physiological effects of soil acidity. In R.W. Pearson and F. Adams (ed.) Soil acidity and liming. Agronomy 12:43-124. ASA, CSSA, and SSSA, Madison, WI.

Jandel Scientific, 1991: Table curve 3.10: curve fitting software user manual. Jandel Scientific.

Jones Jr. J.B. 1989. Soil testing and plant analysis laboratory manual. Benton Laboratories, Inc. Athens, GA.

Jones Jr. J.B. 1991. Plant analysis handbook. Micro-Macro Publishing, Inc. Athens, GA.

Kamprath, E.J. 1978. Lime in relation to aluminum toxicity in tropical soils. In C.S. Andrew and E.J. Kamprath (ed.) Mineral nutrition of legumes in tropical and subtropical soils. p. 233-245. CSIRO, East Melbourne, Australia.

Kamprath. E.J. and C.D. Foy. 1972. Lime-fertilizer-plant interactions in acid soils. IN R.W. Olsen et al. (ed.) fertilizer technology and use. 2nd ed. p.105-151. Soil Sci. Soc. of Am., Madison, Wis.

Kamprath, E.J. 1984. Crop response to lime on soils in the tropics. In F. Adams (ed.) Soil acidity and liming, 2nd ed. Agronomy 12:349-368. ASA, CSSA, and SSSA, Madison, WI.

Li, Z-C, I.P.G. Widjaja-Adhi, T.S. Dierolf, and R.S. Yost. 1996. Liming material selection by computer spreadsheet. J. Nat. Resour. Life Sci. Educ. 25:26-30.

Liebhardt, W.C., 1981. The basic cation saturation ratio concept and lime and potassium recommendation on Delaware's Coastal Plain soils. Soil Sci. Soc. of Am. J. 45:544-549.

MacLean, A.J., and B.J. Finn. 1967. Amendments for oats in soil contaminated with magnesium lime dust. Can J. Soil Sci. 47:253-254.

Martin, J.P. and A.L. Page. 1969. Influence of exchangeable Ca and Mg and of percentage base saturation on growth of citrus plants. Soil Sci. 107:39-46.

McLean, E.O. and M.D. Carbonell. 1972. Calcium, magnesium, and potassium ratios in two soils and their effects upon yields and nutrient content of German millet and alfalfa. Soil Sci Soc. Am. Proc. 36:927-930.

McLean, E.O. 1976. Chemistry of soil aluminum. Commun. Soil Sci. Plant Anal. 7:619-636.

McLean, E.O. 1977. Contrasting concepts in soil test interpretation: Sufficiency levels of available nutrients versus basic cation saturation ratios. In T.R. Peck et al., (ed.) Soil Testing: Correlating and interpreting the analytical results. p. 39-54. Special Publication #29. ASA, CSSA, and SSSA, Madison, Wisconsin.

McLean, E.O. 1982. Chemical equilibrations with soil buffer systems as bases for future soil testing programs. Commun. Soil Sci. Plant Anal. 13:411-433.

McLean, E.O., R.C. Hartwig, D.J. Eckert, and G.B. Triplett. 1983. Basic cation saturation ratios as a basis for fertilizing and liming agronomic crops. II. Field studies. Agron.

J. 75:635-639.

McLean, E.O. and J.R. Brown. 1984. Crop response to lime in the Midwestern United States. In F. Adams (ed.) Soil acidity and liming, 2nd ed. Agronomy 12:267-303. ASA, CSSA, and SSSA, Madison, WI.

Melsted, S.W. 1953. Some observed calcium deficiencies in corn under field conditions. Soil Sci. Soc. Am. Proc. 17:52-54.

Moser, F. 1933. The calcium-magnesium ratio in soils and its relation to crop growth. J. Am. Soc. Agron. 25:365-377.

Nelson, L.A., and R.L. Anderson. 1977. Partioning of soil test-crop response probability. In T.R. Peck et al., (ed.) Soil Testing: Correlating and interpreting the analytical results. P. 1-18. Special Publication #29. ASA, CSSA, and SSSA, Madison, Wisconsin.

Page, A.L, at al. 1982. (Ed.) Methods of soil analysis. Part 2: Chemical and microbiological properties. 2nd ed. Agronomy No. 9. ASA and SSSA, Madison, WI.

Pearson, R.W. Soil acidity and liming in the humid tropics. Cornell Int. Agric. Bull. 30 Cornell Univ., Ithaca, N.Y.

Peedin, G.F., and C.B. McCants. 1977. Influence of variety and soil applications of Ca on development of Ca deficiency in tobacco. Agron. J. 69:71-76.

Prince, A.L., M. Zimmerman, and F.E. Bear. 1947. The magnesium-supplying power of 20 New Jersey soils. Soil sci. 63:69-78.

Reuter, D.J. and J.B. Robinson. 1986. Plant analysis. An interpretation manual. Inkata Press. Melbourne.

Reid, S.W. 1996. Influence of lime and calcium:magnesium ratio on alfalfa and birdsfoot trefoil yields. Commun. Soil Sci. Plant Anal. 27(5-8):1885-1900.

Silva, J.A. (ed.) 1997. Hawaii Soil Fertility Manual. College of Tropical Agriculture and Human Resources, University of Hawaii.

Sims, J.T. and B.G. Ellis. 1983. Adsorption and availability of phosphorus following the application of limestone to an acid aluminous soil. Soil Sci. Soc. Am. J. 47:888-893.

Simson, C.R., R.B. Corey and M.E. Sumner. 1979. Effect of varying Ca:Mg ratios on yield and composition of corn (*Zea mays*) and Alfalfa (*Medicago sativa*). Commun. Soil Sci. Plant Anal. 10(1&2):153-162.

Soil and Plant Analysis Council, Inc., 1992. Handbook on reference methods for soil analysis. Council on Soil Testing and Plant Analysis, Athens, GA.

Soil Conservation Service. 1976. Soil survey laboratory data and descriptions for some soils of Hawaii. Soil Survey Investigations Report No. 29.

Souza, D.M.G., and K.D. Ritchey. 1988. Soil acidity and it's correction. p. 15-32. In 'VI Simposio sobre o Cerrado, Savannas: alimento e energia'. EMBRAPA-CPAC, Brasilia, Brazil. (in Portuguese).

Spies, C.D. 1974. Indiana Plant Food and Agricultural Conference, Lafayette, Indiana.

Sumner, M.E., M.P.W. Farina, and V.J. Hurst. 1978. Magnesium fixation - a possible cause of negative yield responses to lime applications. Commun. Soil Sci. Plant Anal. 9:995-1007.

Swiader, J.M., G.W. Ware, and J.P. McCollum. 1992. Producing vegetable crops. 4th ed. IPP Interstate Publishers, Danville, Illinois.

Tamimi, Y.N., J.A. Silva, R.S. Yost, and N.V. Hue. 1994. Adequate nutrient levels in soils and plants in Hawaii. Fact Sheet No. 3, College of Tropical Agriculture and Human Resources, University of Hawaii at Manoa.

Tisdale, S.L., W.L. Nelson, and J.D. Beaton. 1985. Soil fertility and fertilizers. 4th ed. Macmillan Publishing Co. New York.

Tisdale, S.L., W.L. Nelson, J.D. Beaton and J.L. Havlin. 1993. Soil fertility and fertilizers. 5th ed. Macmillan Publishing Co. New York.

Thomas G.W. 1982. Exchangeable cations. In A.L. Page at al. (Ed.) Methods of soil analysis. Part 2: Chemical and microbiological properties. 2nd ed. P. 159-165. Agronomy No. 9. ASA and SSSA, Madison, WI.

Thomas, G.W. and W.L. Hargrove. 1984. In F. Adams (ed.) Soil acidity and liming, 2nd ed. Agronomy 12:4-56. ASA, CSSA, and SSSA, Madison, WI.

Van Lierop, W., Y.A. Martel and M.P. Cescas. 1979. Onion response to lime on acid histosols as affected by Ca:Mg ratios. Soil Sci. Soc. Am. J. 43:1172-1177.

von Uexkull, H.R. 1986. Efficient fertilizer use in acid upland soils of the humid tropics. FAO Fert. And Plant Nutriion Bulletin, 10. FAO, Rome. 59p.

Walworth, J.L. and M.E. Sumner. 1987. The diagnosis and recommendation integrated system (DRIS). Advances in soil Science 6:149-188.

Walworth, J.L. and M.E. Sumner. 1988. Foliar diagnosis: A review. Advances in Plant Nutrition 3:193-241.

Yost, R.S., 1999. Personal communication.